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POTENTIAL OIL FORMATIONS IN NEW ZEALAND, AND THEIR STRATIGRAPHIC POSITION AS RELATED TO BASIN EVOLUTION*

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ABSTRACT

Seven oil-prospective basins are recognised in New Zealand, and their stratigraphy is reviewed. Potential oil formations, which range in age from Upper Cretaceous to Pliocene, are discussed for each basin. Their particular position in the stratigraphic column is largely controlled by the local tectonic history.

In any one basin, possible source and reservoir rocks are in about the same stratigraphic position and generally closely related to each other. In five of the seven basins, which are characterised as epicontinental, unstable shelf areas, they generally occur near the base of the whole sedimentary sequence; this is shown to be inherent to the paleogeographic setting and particular tectonic evolution, and is consistent with the pattern found under similar conditions in other parts of the world. The characteristic lithologic assemblage of possible source sequences found here is of the shale-sandstone-coal type, and its environment is a transitional one of the near-shore marine and deltaic or estuarine-brackish to freshwater zone.

Additional potential reservoir formations occur in some of the basins higher up in the section. They are formed by sandstone as well as carbonate rocks, and their presence is discussed in relation to the local tectonic history.

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INTRODUCTION

Although New Zealand has produced oil and gas commercially only in Taranaki, potentially prospective formations occur in many areas of both islands. This paper reviews the stratigraphy and, as far as possible, the paleogeography of these areas, and defines and discusses those formations which locally appear to have a bearing on possible occurrence of petroleum.

No complete assessment of the petroleum prospects in the various areas will be given. The structural conditions are not dealt with in detail, nor are potential oil formations discussed with a view to determining their effectiveness. The possible source and reservoir rocks of one area may be far inferior in quality, volume, and distribution to those of another, yet they may be important indicators of the basin evolution. In fact, the occurrence and particularly the stratigraphic position of such formations relative to the local sedimentary sequence, are closely related to the tectonic history of the area. These relationships: (*a*) between possible or probable source and reservoir rocks, and (*b*) their position as compared to the local basin stratigraphy and basin evolution, are the principal features presented here.

When defining possible source rocks, the author is quite aware of the complexity of the concept and the general difficulty which exists for their recognition. In particular, the true amount and the nature of organic matter in the sediments here reviewed have not been determined, and consequently the important factor of the proportion of hydrocarbons to organic matter is entirely unknown. Other important aspects that have not been considered are adsorption and retention of existing petroleum, ratio between free oil and kerogen, amount of compaction and consequent expression of fluids, and availability of suitable interstitial water to act as a vehicle—to name just a few. Only broad geological evidence, and particularly the occurrence of what the field geologist may call "a carbonaceous or bituminous rock sequence", have been used to discuss the relevant implications; but even these rather vague data are believed to be significant, and are useful at least as a means of narrowing down the possibilities of petroleum source strata and their stratigraphic position.

In discussing the occurrence of prospective oil formations, it is necessary to consider the regional tectonic situation, to define local "basement", and to delineate those areas that are structural basins filled with an adequate succession of sedimentary rocks. Seven such basins are recognised (Fig. 1):

North Island—Northland
Waikato
Taranaki-Wanganui
East Coast
South Island—West Coast
Canterbury
Southland

These do not necessarily correspond to original basins of deposition, which often were much more extensive. Local uplift and erosion have reduced many basins considerably, or have disrupted an originally continuous sediment cover so that only relatively small portions remained intact in present-day structural depressions.

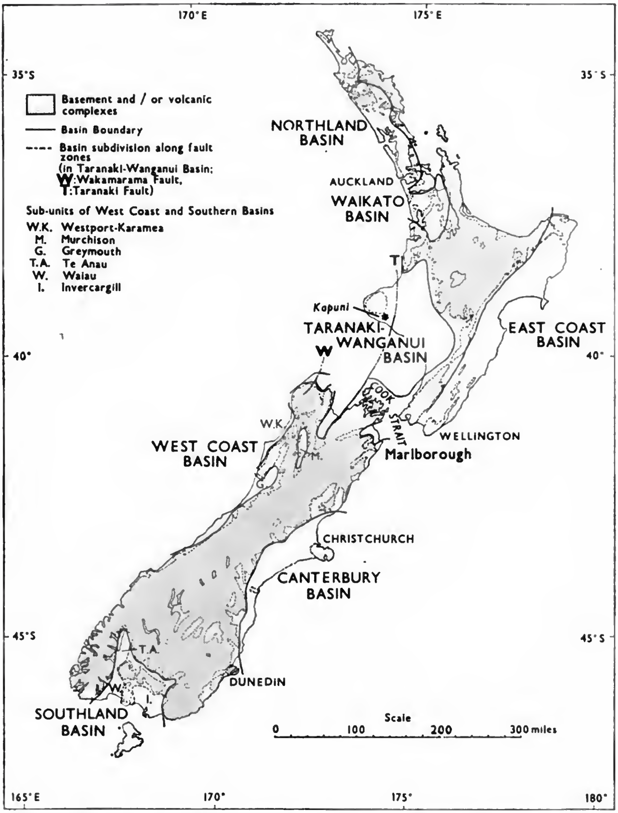

FIG. 1—Map of New Zealand showing the seven oil-prospective sedimentary basins.

As a general feature, the prospective areas are aligned in two sub-parallel belts which are separated by a geanticlinal wedge of Paleozoic and Mesozoic rocks that traverses the entire length of New Zealand. Sedimentary cycles in both the western and eastern troughs are from Upper Cretaceous to Recent in age; but whereas in the east a marine environment dominated throughout the Upper Cretaceous – Tertiary interval, and indeed into the Quaternary, the west is characterised by important terrestrial domains in various areas and stages.

Formations older than Cretaceous are, as a rule, too much indurated in New Zealand to attract an oil geologist's interest. Locally, however, it has been shown that basement reservoirs in such older rocks are possible, and also the possibility of their being source rocks cannot entirely be ruled out.

THE NORTHLAND BASIN

This northernmost basin extends over the entire length of Auckland Peninsula, from south of Manukau Harbour to North Cape. It is limited to the east by basement outcrop of greywacke and argillite, but includes in the north and west the off-shore shelf area with no limit known. Thus it measures at least 8–10,000 sq miles, but 25–30% of it is occupied by volcanic rock complexes.

Folded basement metasediments are Jurassic in the south, and Permian to ?Jurassic in the north-east. Basin-fill is of marine Upper Cretaceous and Tertiary, with mainly dark shale, siltstone, and sandstone, but includes Eocene coal measures, Oligocene limestones, Miocene andesitic grit, and volcanic rocks, as well as extensive sheets of Miocene to Pliocene olistostrome deposits which mainly consist of chaotic breccias formed by Upper Cretaceous to Oligocene sedimentary rocks, and serpentinites; these overlie beds that range in age from Permian–Jurassic to Lower Miocene (Kear and Waterhouse, 1967).

The Southern Portion—Auckland – Manukau Harbour

A distinct basin occupies the Auckland area proper, extending for 70–80 miles north–south along the Peninsula and southwards beyond. Here some 2,000–3,000 ft of Lower Miocene Waitemata beds are the known deposits, which to the east directly overlap basement (Thompson, 1961; Schofield, 1967a); whether or not Lower Tertiary and/or Cretaceous is present subsurface in the west Auckland area and around Manukau Harbour (Schofield, 1967a), is an open question but reported xenoliths of appropriate lithologies in local volcanics (Healy, 1935) and pebbles of argillaceous limestone in Waitemata beds (Park, 1886) would suggest its existence to some extent. Also, both to the north and south beyond the area here considered, and indeed to the east at Drury (Kear, 1959b), Lower Tertiary formations appear at the surface unconformably below Waitemata beds.

In the south the Waitemata Group sequence begins at its base with the marine, glauconitic, and calcareous Waikawau Sandstone (100–150 ft) which locally is replaced by Papakura Limestone. Upwards it passes into the

Koheroa Siltstone (200 ft) which is characterised by the first appearance, within the Tertiary of the area, of volcanic, partly acidic-rhyolitic but predominantly andesitic tuff layers; this in turn is overlain by the Mercer Sandstone (500 ft). Moderately hard and mainly non-calcareous, the Mercer Sandstone is in places rather massive and well sorted, fine to coarse grained, but includes thin carbonaceous mudstone intercalations. Both the Koheroa Siltstone and Mercer Sandstone are, however, only recognised to the south just outside our area (Hornibrook and Schofield, 1963). They are there overlain by the alternating, thin-bedded sandstones and carbonaceous siltstones of the Amokura Formation, a lithofacies that is characteristic of most of the Waitemata Group to the north.

The typical development of the Waitemata beds around Waitemata Harbour, Auckland, has been described in detail by Ballance (1964). According to this author, deposition was in a marine basin within a continental borderland, with rapid eastward overlap of shallow-water and shoreline deposits over a rugged greywacke terrain (Waipapa Group, Permian to Jurassic); the central portion of the basin, of somewhat deeper water and at least 50 miles long by 15 miles wide, is occupied by a turbidite facies of thin-bedded, alternating sandstones and muddy siltstones deposited by mainly south-east flowing turbidity currents which arrived at irregular intervals. This is not unlike a typical flysch sequence, and actually some of the exposed sections near Auckland bear a strong resemblance to flysch deposits as known elsewhere. Westwards, and perhaps upwards, the turbidites pass into tuffaceous sandstone, volcanic grit, and andesitic mudflow deposits (Manukau Breccia) brought into a shallow sea from nearby disrupted and eroded eruptive rocks (Brothers, 1954a); these extend along the west side of Waitakere Hills and through Kaipara Harbour. Submarine flows and pillow lavas occur at Tinopai north-east of Kaipara Harbour, where they are interbedded with fossiliferous, tuffaceous sandstones and conglomerates (Brothers, 1954b); their age, according to latest micropaleontological evidence, is Otaian–Hutchinsonian (Lower Miocene, Scott, 1965). An upwards extension in the stratigraphic column, of coarse volcanic debris above typical Waitemata turbidite sandstones and siltstones is also found in the Cornwallis area on the north shore of Manukau Harbour (Jones and Martin, 1965).

Assuming that in the Auckland area, i.e, in the southernmost portion of the Northland Basin Waitemata beds everywhere rest directly above basement, the possible existence of prospective oil formations is certainly rather limited because of the reduced extension and volume of sediment. Increased subsidence and considerably greater thicknesses could, however, occur in places particularly to the west, and much depends on the exact nature and distribution of depositional environments within this Lower Miocene basin. The turbidites which probably furnish the bulk of the Waitemata beds are not considered prospective, however, in spite of the fact that porosity of individual beds generally is high (Ballance, 1964). On the other hand, the reported large amount of carbonaceous matter in these beds which were deposited in an anaerobic environment (Schofield, 1967a), could provide for ample source material. Particular attention should therefore be paid to the basin flank areas where intraformational sandstone pinchouts and porosity abutments against low-angle unconformities can be expected. The presence of timely traps is of course all important, particularly because in much of the basin sediments appear to have been flushed of original fluids by fresh water (ground-water supply in the Waitemata beds is reported as generally ample or even large; Hay, 1952; Waterhouse, 1966b).

Thus the most suitable reservoir, so far as is known, would probably be provided by the Mercer Sandstone as reported from the south, or any other, equivalent sandstone build-up. The potential source facies occurs in close relationship, both by intercalated or interfingering mudstone and a basinward silt-shale extension, and by the central turbidites which are of the same age and/or slightly younger. According to micropaleontological evidence, all these formations belong to the same Otaian stage, of Lower Miocene age.

If, however, the Waitemata beds were underlain by Oligocene–Eocene and/or Cretaceous (*see* section A–B in Schofield, 1967a), the general prospects of this basin would be greatly enhanced. Increased sediment thickness, existence of unconformities, and a greater variety of suitable facies as well as potential petroleum traps would most likely occur in this area. But since nothing is known about the local development of these formations, little can be predicted about their possibilities. An extrapolation into the Manukau Harbour area of data from the Lower Tertiary Te Kuiti environments as known further south is probably not warranted, but their characteristics will be treated more closely when considering the Waikato Basin.

The Central and Northern Portions

About 50 miles north of Auckland the near-continuous cover of Lower Miocene Waitemata beds terminates, probably mainly owing to erosion. Isolated patches of more or less correlative rocks still occur further north all along Northland Peninsula, though often of greatly reduced thickness and varied lithology; the Otaua Group of Hay (1960) and the Miocene beds in the Waimamaku Valley and around Hokianga Harbour, as well as north of Parengarenga Harbour (North Cape) are the more prominent occurrences, which suggest a one-time much more extensive area of Miocene deposition.

Everywhere along the eastern margin, as far as Waitemata beds extend north of Auckland, they directly overlap basement Waipapa greywacke and argillite (Cape Rodney and Te Arai Point; Thompson, 1961; Hopgood, 1961). To the north and north-west, however, they are unconformably underlain by a sequence of Lower Tertiary which for the first time appears at Dairy Flat (Waterhouse, 1966b) and Wellsford, and which further north continues along most of the remaining portion of eastern Northland as far as Doubtless Bay. This sequence, which rests on Waipapa Group basement rocks, is made up of Eocene Kamo Coal Measures, Upper Eocene Ruatangata Sandstone and Oligocene Mahurangi and Whangarei Limestones; the latter is overlain, possibly with some erosional break at its top, by Waitakian sandstones of lowermost Miocene age (Kear, 1959a). The Eocene–Oligocene thus constitutes a normal transgressive cycle from terrestrial-paralic deposits to widespread open shelf conditions, with extensive crystalline and argillaceous limestones as the typical rock type in its later portion.

The Kamo Coal Measures generally contain two coal seams, each up to 25 ft thick, which are separated by up to 60 ft of carbonaceous sandstone and mudstone. Some sandstone is also found at the base, together with fireclay and rarely some conglomerates. Upwards the Kamo Coal Measures pass without break into the marine Ruatangata Sandstone, up to 200 ft thick, which consists of glauconitic and calcareous grey sandstones with some shell beds and mudstones. Solution cavities seem to be quite common in the calcareous sandstones. From Kamo to the north, it thins considerably and is near Waiomio represented by only 2 ft of conglomerate.

This Northland Eocene–Oligocene sequence just described is best known along the western flank of the outcropping basement greywacke high in the east. Most probably its area of deposition extends across all of the western part of the Peninsula. Oligocene shaly limestones and calcareous siltstones occur near the mouth of Hokianga Harbour, and while Eocene coal measures are restricted to the east, with the exception of the occurrence at Avoca 10 miles north of Dargaville (Healy, 1947), marine middle Eocene (Bortonian) sandstones, siltstones, and shales are known from many areas and in great thicknesses. In a recent drillhole just south of Dargaville (Waterhouse, 1963b) over 900 ft of Bortonian mudstone and silt-sandstone were traversed, without base being reached. In central Northland the Opahi Group (Hay, 1960) is of the same age, consisting of different facies belts characterised by (*a*) glaucontitic greensand and (*b*) argillaceous limestone and green and chocolate shale with flint; both are about 1,000 ft thick. Similar Bortonian rocks have been mapped, and drilled, north-east of Kaitaia in northern Northland (Kear, 1964) where the calcareous siltstones, limestones, and glauconitic sandstones are over 2,000 ft thick, being overlain by another 2,000 ft of Oligocene limestone and sandstone.

However, it has in recent times become more and more evident that much if not all of the older Tertiary and also Cretaceous rocks which so extensively occur across Northland, are only superficial and should therefore be classed in the "Onerahi Chaos Breccia" of Kear and Waterhouse (1967); this particular formation consists of huge exotic masses which by means of large-scale slumping in Miocene–Pliocene times would have reached their present position, partly as still coherent though heavily sheared and broken-up sheets, but more often as a completely mixed chaos of widely different rock units. And while this can actually be proved in many places, it remains to be seen how much of the Bortonian beds mentioned above are really autochthonous. In some places at least, as near Silverdale in the east (Waterhouse, 1963a), the only Bortonian rocks found do in fact belong to the Onerahi Chaos. In the Ngawha deephole, too (Kear, 1966a), Bortonian faunas were found below Upper Cretaceous but mixed with Paleocene and Maestrichtian elements, the whole section down to 1,550 ft, and probably even to basement at 1,750 ft, consisting entirely of sheared and brecciated, mixed rocks of undoubtedly allochthonous origin.

Lower Eocene, Paleocene, and Upper Cretaceous rocks were described by Mason (1953) from the area around Hokianga Harbour, and have more recently been mapped in detail by Hay (1960) in central Northland. Fossil evidence has proven the existence of Cretaceous formations belonging to the Upper Clarence (Turonian), Raukumara (Senonian), and Mata Series (Maestrichtian–Danian), but the general scarcity of good outcrops, due to widespread, deep weathering and low relief, the lithologic similarity between different formations and the rarity of fossils, plus the confusing structural complications have left many unsolved problems as stressed by Hay. His remark (p. 22) that "the Mangakahia beds . . . are so crushed and contorted as to make a structural interpretation extremely difficult" could in fact hint at the possibility that the whole block is part of a dislodged and internally broken up mass and thus perhaps part of the Onerahi Chaos Breccia. The true distribution, structure, and origin of this Onerahi Chaos Breccia, and the uncertain relations of sediments with extensive complexes of volcanic rocks are still the great unsolved problems of Northland geology.

The oldest formation of the cover known consists of hard siliceous sandstone of the Ngaterian stage*, with laminations caused by highly micaceous and carbonaceous bands. Sandstones and siltstones are the main products also of the three stages of the Raukumara Series. The combined thickness of these formations probably amounts to several thousand feet, but no definite figures are available. The Mangakahia Group of uppermost Cretaceous to Paleocene age consists of the following four formations, from base to top:

1. Ngatuturi Claystone. Hard, dark grey to black, siliceous claystones, always intensely folded, crushed and slickensided. No complete section is known, but exposed thickness is 3,000–4,000 ft.
2. Punakitere Sandstone. Micaceous sandstones, partly massive, partly well bedded with some conglomeratic layers, containing plant remains and carbonaceous material, sometimes including thin lenses of coal. Calcareous sandstone concretions up to 6 ft across are common and often include *Inoceramus* fragments. Thickness is 7,000–8,000 ft.
3. Titoki Shale. Grey, green, and chocolate, calcareous shale or argillaceous limestone, up to 2,500 ft thick.
4. Karaka Sandstone. Micaceous sandstone and dark grey shale, 2,000 ft thick.

Beds of the Paleocene to Lower-Middle Eocene Waiomio Group are divided, according to Hay, into three separate facies belts:

(*a*) An eastern belt of multi-coloured shale with flints, probably at least 1,250 ft thick;
(*b*) A central belt of 1,000 to 1,500 ft glauconitic sandstone; and
(*c*) A western belt with shales similar to the eastern ones, but without the flints, possibly 350 ft thick.

The Opahi Group of Middle to Upper Eocene age has been mentioned above already and is of a very similar lithology and facies distribution.

Thus the total thickness of Upper Cretaceous to Lower Tertiary sediments in Northland would easily amount to 14,000 ft; but, as should be stressed again, it is obvious that such a figure is very tentative only, as most sections in the field are isolated, incomplete, faulted, and otherwise tectonically complicated. In addition, there remains the principal problem as to how much is actually autochthonous, and how much is exotic, having come to its present position by long-range sliding (?or partly thrusting). More and more data are accumulating which support such a condition and a number of drillholes from Lake Ohia in the north across central Northland down to Kaipara Harbour in the south have indeed found Tertiary beds underlying the Cretaceous (Waterhouse, 1963b, 1966a; Kear, 1966a; Kear and Waterhouse, 1967; pers. comm. on recent drill holes near Batley, by Mr B. N. Thompson, New Zealand Geological Survey).

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*For the classification of N.Z. Cretaceous stages see Wellman, 1959.

It is furthermore noteworthy that much of these sediments is of a very distinct facies type which in itself raises a suspicion that they originated elsewhere. Thick, monotonous dark shales which often are highly siliceous, as well as argillaceous limestones and particularly the green and chocolate, multi-coloured shales associated with flints, are deposits which do not commonly occur in miogeosynclinal mixed shelf associations such as would normally be expected here in the light of simple paleogeographic considerations. And while the Upper Cretaceous and Lower Tertiary deposits, although occurring close to what is probably the eastern limit of the depositional basin, are typical, in Kündig's (1959) classical notion, of a perennial, eugeosynclinal environment, they would appear truly exotic in their present position close to a continental borderland. The occurrence of ophiolites associated with these sediments in Northland lends strength to this assumption. Although the age and provenance of the ophiolites is as yet unknown—they always form rootless bodies of serpentinite embedded in Onerahi Chaos Breccia—it seems probable that they are related to the formation and existence in this area of the olistostrome masses themselves, as happens in many other places. In general characteristics, at least, the areas of Onerahi Chaos Breccia seem to bear a striking resemblance to exotic block zones in the northern Himalayas, for instance, or the so-called "Coloured Melange" suites in Baluchistan and Turkey (Bailey and McCallian, 1953; Gansser, 1959).

As in the latter area, the Onerahi Chaos Breccia (which in some places perhaps is comparable to a "block-flysch" or the alpine "wildflysch") appears closely associated with normal flysch sequences, as in the south for instance, where it directly overlies the Waitemata flysch series, but may possibly also form tongues and wedges within it (Dr D. Kear, pers. comm.).

These problems naturally are of prime importance with respect to petroleum possibilities and exploration. The Cretaceous to Lower Tertiary series, which apparently cover the greater part of Northland Peninsula, seem to be very thick and include various sandstone formations which could have, locally, good reservoir characteristics. The bulk of these deposits, on the other hand, is formed by carbonaceous shales and dark mudstones which are probably potential source beds. Several oil shale occurrences have been mentioned, too, at least three of them yielding upon distillation oil at 26 to 50 gallons per ton (Elphick, 1959). But no good oil seepages are known, except for the indications at the Ngawha hot springs (Bell and Clarke, 1909). Numerous gas seepages are known throughout Northland, several of them containing considerable amounts of methane (up to 95%) and some also fractions of higher hydrocarbons (Ross, 1967); but no gas truly associated with petroleum is known, gas from such seeps as have been tested being marsh gas (Watt, 1965).

The fact that rock areas mapped as Upper Cretaceous, however, are at least in some places actually olistostromes which in part are extremely broken up, forming incompetent, chaotic breccias of highly mixed components, would probably diminish their petroleum potential substantially. There is a possibility that such Cretaceous rocks, even where representing dislocated gravity slides, could still have retained their potential, provided they form coherent nappes with traps formed at the right time and at suitable places. On the other hand, the recognition of olistostromes made up of Cretaceous to Lower Tertiary might well enhance the general prospects of the area, in which Upper Eocene to Miocene consequently can be expected in subsurface (Kear and Waterhouse, 1967). This means that large areas which in Northland are covered by Cretaceous may have Tertiary prospects in subsurface formations that represent the basin-ward extension of known Eocene to Oligocene and/or Lower Miocene deposits which outcrop further to the east. Facies pattern and environment distribution of Kamo Coal Measures, Ruatangata Sandstone, Whangarei Limestone, as well as Waitakian sandstones and their correlatives thus become important. Westwards away from the basement high in the east, one might envisage therefore Tertiary conditions similar to Taranaki and other West Coast provinces, although surface geology interpretation perhaps erroneously has led geologists to compare Northland conditions with those on the East Coast (Quennell, 1965).

Thus, if autochthonous Tertiary beds lying underneath olistostrome depostis composed of Cretaceous to Lower Tertiary rocks, must definitely be included now in the general prospects, the question arises whether these Tertiary beds everywhere overlap basement, or whether they are underlain again by another sequence of Upper Cretaceous sediments. This is entirely a problem of subsurface exploration, and no data for its solution are as yet known. There are, however, Cretaceous mudstones, sandstones, and conglomerates exposed in many places along the north-east coast from Mt Camel to Karikari Peninsula and Whangaroa Bay (Kear and Hay, 1961; Hay, 1968); they are Motuan in age, thus Albian and would probably have to be included for the purpose of oil geology in the Waipapa basement complex, but this, too, needs confirmation.

In conclusion, it appears that Northland is still too little understood geologically for any definite statements to be made. But it does offer a variety of potentially favourable conditions, and prospective formations may well be found, if not in surficial Cretaceous, then at least in the buried, autochthonous Tertiary and/or Cretaceous which in addition is probably less complicated tectonically. As has been shown in other areas, subsurface exploration through a thick cover of chaotic olistostrome accumulation is quite possible by a careful interpretation of data available through conventional exploration tools; promising structural highs in the underlying normal sedimentary series have actually been located, and proven by drilling, through more than 5,000 ft of olistostrome deposits in Sicily (Flores, 1959).

Potential oil formations thus should be looked for not only in the Cretaceous, although it is extensively mapped at the surface and appears to include a particularly promising facies. Where such Cretaceous rocks form part of the Onerahi Chaos Breccia, oil may exist in any normal sedimentary sequence underneath, most probably of Tertiary age; in general, oil may be both of Tertiary and/or Cretaceous origin, while the particular tectonic conditions would be especially favourable for pools found by secondary migration, in addition to primary ones. Apart from various shaly formations, the impervious cover of the Onerahi Chaos Breccia would certainly provide an excellent seal.

THE WAIKATO BASIN

The area extends south of the Pukekohe basalt complex, i.e., covering the lower Waikato River – Huntly area, plus the Hamilton and Hauraki basins, and is thus one of the more restricted of potential oil basins in New Zealand, both in its size and geologic conditions. It measures about 3,500 sq miles but considerable portions within it are occupied by basement outcrop. Certain subsurface information is available from coal and oil exploration, and recent summaries on the general geology have been published by Lehner *et al.* (1965) and Schofield (1967b).

Basement rocks are Triassic–Jurassic, folded greywacke metasediments (Kear, 1960; Schofield, 1967a), which have been eroded and levelled following the post-Hokonui orogeny. Subsequent sedimentation was not renewed until the Upper Eocene, when the Waikato Coal Measures were deposited. These freshwater beds constitute the basal formation of the Lower Tertiary Te Kuiti Group of Kear and Schofield (1959), and have been deposited in local depressions of a varied landscape. Tectonic unrest and faulting seem to have affected their distribution and thickness which, including non-marine mudstones, sandstones, and conglomerates, ranges from virtually nothing to 1,000 ft. Yet they are clearly restricted to a structurally-formed long, narrow trough which subsequently widened; younger formations further and further overlap to the west and to the east as well as to the south. The whole sequence passes upwards through estuarine mudstone and sandstone to open water, marine sand-silt-mudstone and limestone. The sea, however, always remained shallow, and lateral facies change thus mainly reflects distance from shore line. The Oligocene flaggy limestone, for instance, which is formed of comminuted shell fragments and coarse sand, is persistently a near-shore deposit, whereas silt-mudstone occurs farther out in the basin. In the south, the Elgood Limestone attains a maximum thickness of 100 ft (Kear and Schofield, 1959). With subsequently diminishing supply of clastic material from land, crystalline limestone containing large oysters, pectens, and numerous brachiopods was formed (Otorohanga Limestone, up to 200 ft thick). A relative increase in calcium carbonate content towards younger sediments is also noted in siltstones, which occur nearer the centre of the basin, as for instance between the older Whaingaroa and younger Te Akatea Siltstones.

The age range of the Te Kuiti Group sediments is from Upper Eocene to Lower Miocene, but no beds younger than Oligocene are known in the region here discussed: Miocene is restricted to a more southerly portion. An unconformity reflecting a considerable erosional break separates the

Te Kuiti Group from the overlying Waitemata Group of Lower to Middle Miocene age (Hornibrook and Schofield, 1963). Block faulting and dislocation of Te Kuiti beds resulted in their being removed down to the Mangakotuku Siltstone in certain places of the Hamilton area, and probably in their complete destruction in areas nearby. Coal pebbles from the Waikato Coal Measures, up to 4 in. long (Kear, 1961), as well as Glen Massey Sandstone and greywacke boulders (Schofield, 1967b) are reported from the basal Waitemata sandstones. A detailed description of the remaining sequence in the Ngaruawahia Subdivision, which covers the main part of the Waikato Basin as here discussed, is presented by Kear and Schofield (in press; see also 1964). The average thickness of the Te Kuiti Group in this area is given as 1,350 ft.

The overlying Waitemata Group is stated by the same authors to be 2,000 ft thick, and is developed as already described for the southernmost portion of the Northland Basin. Its paleogeography and the inter-relation of different formations is still not well understood, but a generally shallow-water to deltaic environment can be suggested for most of this region.

Another unconformity separates the Waitemata Group from the Pliocene–Quaternary beds of the Tauranga Group (1,000 ft), which is dominated by terrestrial sediments (clay, lignite, peat, sand, and gravel), and particularly by materials of rhyolitic provenance derived from the Central Volcanic Region (pumice sand and silt, also ignimbrite sheets). Andesitic and basaltic rocks, partly in well preserved cones, are spread throughout the area.

Strong vertical displacement has occurred after Waitemata deposition, and many topographically high areas show basement outcrop partly covered by erosional remnants of Te Kuiti Group sediments, and/or Waitemata beds. Only in parts of the lower Waikato north of Huntly, and in parts of the Hamilton and Hauraki lowlands are these formations buried and more or less intact, thus offering prospects for the oil geologist.

In these areas, one can expect porous horizons in both the Te Kuiti and Waitemata Groups, with possible traps formed by structural and stratigraphic conditions, sandstone wedge-out, porosity abutments, and unconformities. In the Te Kuiti Group several porous sandstone as well as limestone members are locally known. Oil slicks and gas have been reported within the Mangakotuku Siltstone in a drillhole at Mercer, at depths of 742 to 1,040 ft (Lehner, 1965). This formation, together with the Pukemiro Sandstone below, belongs to the mainly marine-estuarine lower portion of the Te Kuiti Group, overlying the Waikato Coal Measures. Gas (mainly methane) has frequently been encountered in several drillholes, and is probably directly derived from the coal. Recent investigations by the Chemistry Division, DSIR, have shown pressure build-up and gas emanating from coal cores from Huntly, even long after they had been recovered from the borehole and sealed off in airtight containers in the laboratory; the gas contained up to 58% methane (calculated air-free) plus traces of ethane, the remainder being mainly nitrogen (Miss J. B. Ross, pers. comm.).

As the coal measures appear to become somewhat younger from north to south (and locally perhaps also from west to east across the Hakarimata Range), the Kemps Coal Seam near Whatawhata and Karamu probably is equivalent, stratigraphically, to the Pukemiro Sandstone of the Glen Massey Coalfield further north (Kear and Schofield, 1965). It is underlain by the Whatawhata Sandstone which is described as a medium to coarse, highly quartzose, light grey–white carbonaceous sandstone up to 40 ft thick; this latter particularly seems to be suitable for building up a substantial reservoir body, provided it is found in an appropriate location. The Whatawhata area is therefore the more interesting, as it is directly adjacent to the Waipa Fault and thus nearest to the corresponding sequence buried underneath the Hamilton lowlands. This fault, which is inferred to be transcurrent (Kear, 1960), evidently produced a considerable vertical displacement, too, in post- Coal Measure times. The base of the Te Kuiti Group is from a few hundred to over 1,000 ft above sea level in the Kapamahunga Range immediately west of the fault, but is over 5,000 ft below in the Te Rapa–1 well drilled recently in the adjacent western part of the Hamilton basin, by N.Z. Petroleum Exploration Co. Ltd. (well reports at N.Z. Geol. Surv., open file). It has furthermore been suggested (Lehner, 1965) that the formation of this basin was already initiated during or before Coal-Measure times, so that even thicker Te Kuiti beds could be expected here. As it is, drilling proved the Te Kuiti Group to be 689 ft thick in the Te Rapa–1 well which, according to seismic and gravity information, is located in the deeper parts of the basin; no porous horizons were apparently found in the well section of the Te Kuiti beds (Fig. 2).

No oil or gas indications are known in the Waitemata beds. But evidently, some of the thick sandstones would be excellent reservoir rocks, if encountered subsurface in areas such as the Hamilton or Hauraki lowlands. Unfortunately, the only well which crossed the entire section, Te Rapa–1, found 2,721 ft of Waitemata beds virtually devoid of porous members, the Mercer Sandstone hardly being recognisable in the electric log. Only near the base three somewhat more appreciable sandstone bodies appear to exist (?Waikawau Sandstone), of which the lowermost and thickest (4,608 to 4,721 ft) shows the greatest porosity corresponding with three to four narrow, high resistivity peaks (Fig. 2). We know of no test made here. The age of most, if not all, Waitemata beds in the Te Rapa–1 well is (Dr N. de B. Hornibrook, pers. comm.) Upper Pareora to Altonian (Middle Miocene). This is somewhat younger than the age of the Waikawau Sandstone at its type locality (Hornibrook and Schofield, 1963), or of the Waitemata Group in the Auckland Basin further north (*see* p. 1082).

As to possible source rocks, the most likely formation is the Waikato Coal Measures of Upper Eocene age, either by generating oil or gas directly from the coal (Rogers, 1965), or by providing a source from its associated sediments deposited in a transgressive environment across an initially landlocked area. Organic content was evidently appreciable, and anaerobic conditions persisted up into the Mangakotuku Siltstone (Kear and Schofield, 1959). Source rock quality in the Waitemata Group is believed to be inferior although locally, judged by its facies further north in the Auckland Basin, mudstones rich in organic content may also be present to act as a source for possible oil and gas indigenous to Miocene sediments.

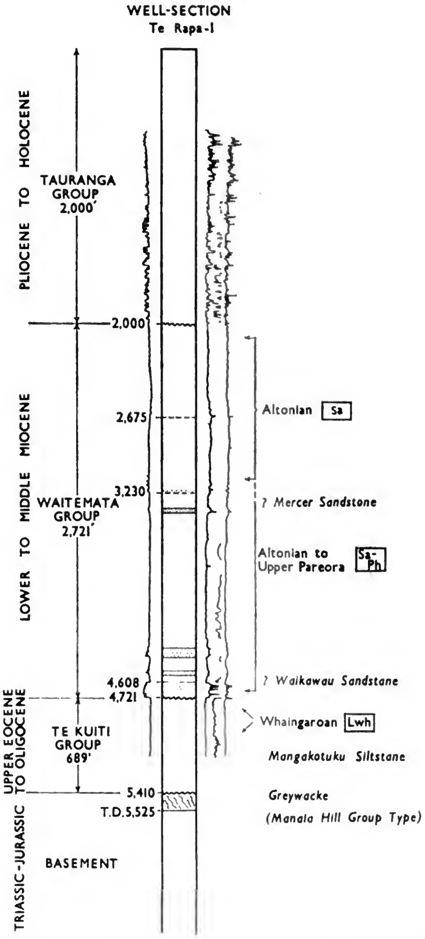

FIG. 2—Well section of Te Rapa 1 drilled in 1964 by New Zealand Petroleum Exploration Co. Ltd, north-west of Hamilton, Waikato Basin. Age determinations from forams by Dr N. de B. Hornibrook.

THE TARANAKI–WANGANUI BASIN (COOK STRAIT TO NORTH-WEST NELSON)

General

This is one of the largest of the young sedimentary basins in New Zealand, and has some of the thickest Tertiary successions. Also, it is the only one so far where hydrocarbons in commercial quantities have been found (Motorua oil field, New Plymouth, and Kapuni wet gas field). Although little information is published, this is undoubtedly by far the best explored of all Tertiary basins in New Zealand. Its size on land measures about 8,000 sq miles but, including portions of Cook Strait, Tasman, and Golden Bays in Nelson which appear to be off shore and South Island extensions of it, well over 16,000 sq miles can be assessed, while still more may belong to it on the continental shelf further west.

Most of the basin is covered by young, Plio-Pleistocene sediments and Recent volcanics (Mt Egmont, etc.). Older Tertiary rocks crop out only towards its northern margin, and between Nelson and Cape Farewell in the South Island. Only geophysical work and drilling have therefore revealed the particular subsurface condition which basically shows two very different areas, separated by the Tongaporutu–Patea basement high with the large Taranaki Fault along its western side (Lensen, 1959; Cope and Reed, 1967). West of the Taranaki Fault, basement is downthrown 20,000–25,000 ft and covered by an almost complete succession from Eocene to Recent (Cope and Reed, 1967). East of the fault, however, no Eocene beds are known, and while here the Oligocene and Miocene are restricted to the so-called "North Wanganui Basin" (Cope and Reed, fig. 9, 1967), the "South Wanganui Basin" contains a thick sedimentary fill of exclusively Plio–Pleistocene age, which on seismic evidence reaches 17,000 ft in the "Turakina Syncline" (Fleming, 1953, p. 297). This recent subsidence of the Wanganui Basin in general is marked by a strongly negative gravity anomaly, which is one of the most pronounced gravity features of New Zealand as a whole (Reilly, 1965).

The pre-Tertiary basement is exposed north and east of the basin, and consists of Triassic–Jurassic sandstone, silty mudstone, greywacke, and argillite of both the "Hokonui" and "Alpine" facies of the New Zealand Geosyncline (Wellman, 1956). The cores of all the wells that reached basement show from west to east a gradual change from shelf to axial facies, with a clearly discernible increase in metamorphic recrystallisation (Cope and Reed, 1967). The basement west of the Taranaki Fault has not been reached, but according to Cope and Reed it probably consists of Lower Paleozoic sediments and granite, comparable to the prevailing basement rocks in north-western Nelson; in the latter area, which can be considered the direct southern continuation of western Taranaki, an older, largely "stabilised" pre-alpine structural element, including large granite masses, is overlain immediately by the deposits of Tertiary transgression (Grindley, 1961).

However, the Mesozoic of the western Hokonui shelf facies, and particularly the higher beds of the Kawhia Syncline north of Taranaki which are supposedly present beneath part of the Tertiary basin, may not yet constitute a basement but, on the contrary, could be a prospective element in

TABLE 1—Stratigraphic Sequence of Exposed Tertiary Sediments in Taranaki

after Hay (1967), and Suggate (in prep.)

		N.Z. Stages			Thickness in Feet (in type area)
PLIOCENE		W_o–W_w		*Tangahoe Mudstone:* Sandy mudstone with concretions, near top thin sandstone beds intercalated.	2,000
		T_k–W_o		*Matemateaonga Sandstone:* Shallow water sandstone and lesser mudstone, with numerous conglomeritic shellbeds.	9,000
MIOCENE	Upper	T_t		*Urenui Siltstone:* Micaceous siltstone with some concretionary layers and conglomerates containing granitic pebbles from westerly source.	1,500
		T_t		*Mt Messenger Sandstone:* Banded mudstone with tuffaceous sandstone, overlain by argillaceous sandstone with concretionary bands.	2,400
	Upper to Middle	T_t–S_l	Mohakatino Group	*Tawariki Claystone:* Claystone with thin tuffaceous lenses and sandstone bands.	300
				Ferry Sandstone: Green, non-tuffaceous sandstone with some claystone bands.	200
				Purupuru Tuff: Highly tuffaceous claystone up to 50 ft, overlain by claystone containing thin tuffaceous lenses. Locally contains the foraminiferal Patokatoka Limestone, up to 30 ft thick.	150
				Mangarara Sandstone: Sandstone underlain by thin conglomerate. Locally contains lenses of Waipapa Limestone up to 100 ft thick.	10–150

MIOCENE	Middle to Lower	P_a — P_h	Mokau Group	*Upper Mokau Sandstone:* Marine muddy sandstone, well bedded, with conglomerate and shell lenses at various horizons.	550
				Maryville Coal Measures: Upper and lower zones containing coal seams, separated by 50 ft of massive carbonaceous sandstone.	200
				Lower Mokau Sandstone: Massive muddy sandstone. Coal measures with a thin and impersistent seam towards the base.	400
	Lower	P_o — L_w	Mahoenui Group	*Upper Awakino Limestone:* Foraminiferal limestone, only locally developed.	0–20
				Mahoenui Mudstone: Mudstone, in part massive (current bedded) and in part alternating with sandstone (graded bedded).	750
				Lower Awakino Limestone: Foraminiferal limestone with some greywacke pebbles.	0–100
OLIGOCENE		L_d — L_{wh}	Te Kuiti Group	*Te Kuiti Limestone:* Hard cream-coloured crystalline limestone consisting of Bryozoa, echinoderms and Foraminifera. Current bedding and platy structure. In NE, possible lateral equivalent: *Mangapehi Sandstone.*	20–250
				Whaingaroa Siltstone: Blue calcareous siltstone (in NW).	0–200
				Waikato Coal Measures: Carbonaceous sediments containing coal seams, usually thin, but at Bennydale 8–20 ft thick.	0–50

the search for oil. Over 15,000 ft of Jurassic alone (Fleming and Kear, 1960), with thick sequences of marine mudstones, siltstones, and sandstones, could at first appear rather attractive, for they are very little indurated, and were never buried beneath an excessive pre-Tertiary overburden, nor are they very strongly folded or otherwise deformed. No source rocks of any suitable quality, however, are present in the whole succession; and while some sandstones are porous and could possibly serve as a potential reservoir, the absence of such source beds, and particularly the large erosional interval subsequent to Early Cretaceous folding, are factors which can only imply that these rocks effectively are "basement". There could exist, nonetheless, some fossil topographic highs with suitably porous rocks which, after being covered by younger strata, would be capable of storing Tertiary oil and thus of acting as a "basement reservoir".

Marine Cretaceous is not known from anywhere in western New Zealand and is, therefore, probably absent underneath the Taranaki Basin. Transgression starts, in the northern outcrop area, with Oligocene Whaingaroa Siltstone and Te Kuiti Limestone, underlain locally by thin carbonaceous sediments containing coal seams, which have been correlated with the Waikato Coal Measures.

From the stratigraphic succession presented in Table 1, it follows that the Oligocene–Miocene has a combined thickness of some 7,000 ft, but great variations of both thickness and lithology occur. As the overall structure is a south- to south-west-dipping monocline, however, such variations can only be studied in an east–west direction. Little information is obtained from surface geology about variations in a north–south direction, but well sections indicate that the Mahoenui beds alone increase to about 7,000 ft in the area of New Plymouth, while at the same latitude the Upper Miocene sandstones and mudstones measure about 5,000 ft; they have been proven to be 3,000 ft thick in the Midhurst, Kapuni, Mangahewa, and Inglewood wells (Lehner *et al.,* 1965). Also, most formations are strongly diachronous throughout the area.

During the history of the basin, it apparently became differentiated into several units each with a distinctive stratigraphic and structural record, and this situation must have increasingly contributed to the generally complex conditions. The presence of growth structures, both as anticlines and faults, is suggested from various information, and some of them appear to be active to the present day (cf., Marton and Mt Stewart anticlines and well sections, Feldmeyer *et al.,* 1943; Te Punga, 1957). In particular, the Patea–Tongaporutu Basement High was probably active for a very long time from the Eocene onwards, while more or less simultaneously the Kapuni anticline in front of it gradually rose, but ceased to be active before Middle to Upper Miocene (Watt, 1965). The Uruti wells which were drilled on the High itself some distance further north penetrated only a reduced section of Miocene before reaching basement (Lehner *et al.,* 1965), whereas to the south not even Miocene is present on this High; here the Pliocene Wanganui Series apparently transgressed the uplifted block (Lensen, 1959). This structure has since remained dormant, but was still perhaps partly emergent, or at least very shallow, during the Lower Pliocene, as is suggested by sedimentary facies distributionn (Lehner *et al.,* 1965). General tilting of the whole basin and shift of its axis continued, after the

Upper Miocene, progressively southwards. East of the Patea–Tongaporutu High, the large Wanganui Basin proper came into being due to strong subsidence of the area between Wanganui and the Ruahine Range. Pliocene sediments at least 15,000 ft thick have been measured in the Rangitikei Valley by Superior Oil Co. geologists (Feldmeyer *et al.*, 1943; Fleming, 1953), on top of which another few thousand feet of Lower to Middle Pleistocene beds are found, still partly marine. Fleming (1953) has described and discussed in much detail this succession, establishing or redefining a number of stages, groups, and formations.

In southern Taranaki west of the Patea–Tongaporutu High, a thick subsurface sequence of Eocene sandstones with interbedded clays and coal seams was found below the Mahoenui and Te Kuiti Group sediments (Kapuni wells, Inglewood–1, etc.; Watt, 1965). In the type section, this Kapuni Formation is more than 3,000 ft thick, and over 4,600 ft of it were penetrated in Inglewood–1 (Suggate, 1965); but basement has not been reached. The age from pollen is mainly Bortonian–Kaiatan, but may reach up into Runangan (McIntyre and Harris, 1961; McIntyre, 1962; McIntyre and Norris, 1966a); it is thus wholly Upper Eocene. The deposits are said to be lagoonal to deltaic near the edge of the encroaching Eocene sea. Although the sediments are mainly of freshwater origin, it has been argued that a marked increase in organic sulphur about 2,500 ft below the top of the Kapuni Formation, both in the Kapuni–2 and Mangahewa–1 wells, indicates marine conditions during deposition of these beds (Suggate, 1965); the presence of dinoflagellates in Inglewood–1 still further down in the section, at a depth of 15,200 ft or 3,200 ft below the top of the formation, provides further evidence of a marine, perhaps brackish estuarine origin of the corresponding shales (McIntyre and Norris, 1966a); no coal was encountered in Inglewood–1 between 14,650 ft and 16,600 ft, i.e., in the lowermost 2,000 ft (Suggate, 1965).

As transgression progresses further to the north, the Kapuni Formation apparently becomes gradually younger and passes laterally into the Waikato Coal Measures and Mangapehi Sandstone of the Te Kuiti Group, which together represent its facies equivalent in the outcrop area to the north. Sediment transport was evidently from north and north-east, at least up to the Middle Miocene, and although the Oligocene formations can be traced continuously through to the Waikato, there was, most of the time, a narrow threshold between the two basins, which generally was very shallow and at times even emergent (the "Piopio Threshold", Hay, 1967).

Southwards the Taranaki Basin is supposed to be continuous across the western Cook Strait and into northern South Island. Here tectonic disturbances have been stronger, however, and the Lower Pleistocene gravel cover is extensive; only minor remnants of the Tertiary sedimentary sequence are exposed around Tasman and Golden Bays. The basal portion again consists of (Upper) Eocene coal measures, the so-called "Quartzose Coal Measures" of Suggate (1950) which, east of the Wakamarama Fault, rest on Paleozoic sedimentary, metamorphic, and igneous rocks. Their thickness varies considerably over very short distances from 0 to 1,600 ft, and while this could suggest subsequent tectonic movement and erosion, the coal measures pass upwards with no observable break into Oligocene marine beds (Suggate, 1950). Upper Eocene in a marine facies is known from a poorly exposed, vertical series near Nelson City, consisting of a fossiliferous, dark and massive, marly mudstone with calcareous concretions (Bruce, 1962). Upwards the Eocene passes into Oligocene to Lower Miocene limestone and calcareous, argillaceous siltstone which locally grade into glauconitic sandstone. These beds are overlain with a possible break and disconformity by Altonian (Middle Miocene) mudstone (Sprigg *et al.*, 1965). The total thickness of Oligocene–Miocene sediments in these landward areas is little more than 1,000 ft, but possibly it is somewhat reduced tectonically due to drag and faulting in these complex graben-type structures which form the southern extension of the Golden Bay and Tasman Bay embayments. Northward, however, the thickness increases rapidly, as the basement is plunging off shore (Officer, 1959), and seismic investigations have recorded a Tertiary sediment thickness of 6,000–11,000 ft off Farewell Spit (Sprigg *et al.*, 1965).

West of the big Wakamarama Fault, the Cape Farewell peninsula is formed by an uplifted and tilted basement block covered with thick Upper Cretaceous coal measures. This Pakawau Group (Suggate, 1956) is formed by 5,000 ft of Maestrichtian (Couper, 1960) freshwater conglomerates, sandstones, and mudstones with local coal seams, which rest on Paleozoic basement which includes granite intrusions. Apparently there is no break upwards in the sedimentary succession, the uppermost portion of the Pakawau Group (Farewell Formation, 600 ft) probably being Paleocene and Eocene in age and thus correlating in part with the "Quartzose Coal Measures". It is, in turn, conformably overlain by the marine, glauconitic sandstones, mudstones, and limestones of the Oligocene to Lower Miocene Westhaven Formation. Thus this uplifted block to the west represents a separate province with respect to tectonic evolution, and as such may well extend further north along the western shelf, perhaps as far as off-shore Taranaki.

The Distribution of Prospective Oil Formations

As this comparatively large area comprises several blocks, each with a very different history, the presence and characteristics of potential source and reservoir rocks, too, will be controlled to a great extent differently in the various sectors. The deposition of formations and the distribution of facies have continuously been influenced by contemporaneous tectonic activity over much of the area; growth faults have been active over long periods, and slowly growing anticlines have contributed to the complex conditions, which can be traced here only along very general lines.

As migration of oil from older Tertiary formations would have been limited by the major faults, and influenced also by the generally southward tilting of the blocks, prospects in the *South Wanganui Basin* are restricted to the Pliocene not only in respect to potential reservoirs, but also regarding the source of the oil*. As the Pliocene in general was a period of persistent shallow-water conditions in this area, numerous clean, porous sandstones have resulted. Differential subsidence, periods of stand-still and local emergence with consequent shore-line migrations, and deposition of shoal and beach sands, shell beds, and other strand-line deposits (Fleming, 1953) must have contributed to establishing excellent conditions for stratigraphical traps. Several thick, impermeable siltstones and mudstones should form adequate cap rocks for possible oil and gas accumulations, while total thickness and overburden must, beyond doubt, have provided favourable conditions for the generation of hydrocarbons, if source rocks are present in the lower part of the section. In fact, porosities of over 30%, with permeabilities around 400 millidarcies, have been measured by Superior Oil Co. (Feldmeyer *et al.,* 1943) in the Lower Pliocene, particularly of the Rangitikei Valley to the east, and the intercalated Taihape Mudstone was considered a most likely source rock.

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*This holds true unless Middle to Lower Tertiary exists somewhere downdip off shore to the south-south-west. This, however, is not very likely, and nothing is at present known from that area apart from the existence of a Lower Tertiary faulted outlier at Otaihanga near Paraparaumu, and another one at Picton.

However, it is mainly this question of the presence of adequate and sufficiently widespread source material which here is disputable. As it appears, the overall picture of the Pliocene succession in the Wanganui Basin with its generally well agitated shallow water environments, providing a good oxygen supply for most of its sediments, probably is not favourable for the formation of oil source rocks. On the other hand, the negative results of the four deep holes drilled in the southern part of the basin do not seem to disprove entirely its chances of containing local oil accumulations elsewhere. These wells are located on basement highs where, as is particularly the case with the Superior Oil Company's Stantiall–1 and Young–1 wells, the sedimentary section is considerably reduced, lower members being developed in brackish to littoral facies and/or cut out completely, so that it may well be that these structures are just buried topographic hills. However, there is also the possibility of folding and faulting being contemporaneous with sedimentation, and therefore much thicker and more complete sections, including potential source rocks, might be expected down-flank in the deeper, synclinal parts of the area. Consistent with this interpretation are the seismic contour lines which indicate a flattening of structural features higher in the section, i.e., increased closure with depth and up to 14,000–17,000-ft-thick sections adjacent to structural crests. This, admittedly, could also be due to a draping effect over buried hills, but the very sharp basement relief and the shape and dimensions of these structures suggest a tectonic origin contemporaneous with deposition, rather than their being the product of pre-Pliocene erosion and basement topography accomplished before subsequent burial. The present-day active growth of these and other structures in the area (Te Punga, 1957) is consistent with this picture, and points to continued tectonic activity of the same kind, even at an accelerated rate in Recent times as compared with the Pliocene and Pleistocene.

This particular situation—a structurally distinct area with locally restricted but well pronounced troughs and highs, which possibly are pre-sediment intra-basement features but most probably were growing during subsequent sedimentation—is definitely thought to warrant further investigation. Thick sections of Lower Pliocene are indicated by seismic evidence only a short distance away from the highs; here conditions may have been favourable for the formation of source rocks, while stratigraphic traps up-dip on the flank of the structures could be present and constitute a most likely target, but none of these deeper parts has ever been tested.

In this area there is, in addition, the problem of flushing. From the basal sand in Stantiall–1, at 6,800 ft, a small quantity of very fresh water (428 p.p.m. of NaCl) was recovered, while upon testing with a formation tester at Young–1, sands between 3,125 ft and 3,155 ft which had given off a very faint petroliferous odour when first cored, recovered water with no obvious gas cuttings and 3,420 p.p.m. of NaCl. With the intake area to the north and north-east and a regional dip to the south-south-west, it has been concluded that flushing occurs in this direction. If, therefore, entrapment under hydrodynamic conditions prevails (King Hubbert, 1953), a tilting of any oil/water contact could result, or even displacement of oil accumulations to the southern sides of structures. Also, it might be expected that stratigraphically lower sands which only exist in the deeper parts and wedge out against the highs would not be affected by this flushing. Quite generally under these conditions, centre areas of the basin could still yield oil even if structures near the border of the basin are devoid of it, because all their original content of hydrocarbons (and salt water) have been displaced.

In the *North Wanganui Basin,* the basement is overlain by Oligocene and/or Miocene (Cope and Reed, 1967, fig. 9; Hay, 1967). Erosion has cut well down into the sequence here, and the only prospective rocks are found in the Miocene Mokau Group and possibly in some basal sandstones of the Te Kuiti Group, which correspond to the productive Kapuni Formation in the southern Taranaki Basin. The Te Kuiti Limestone where it is mainly composed of shell fragments can be considered a possible, although poor reservoir rock, but it appears to shale out towards the south. During the Upper Miocene, on the other hand, sedimentation was rather rapid and the various sandstones therefore too argillaceous to form good reservoirs.

The Mokau sandstones which particularly are developed in the west, are well bedded to massive, marine sandstones of fair to good porosity and widespread extension. A western sediment source (Tasmantis) began at this time to be influential, while to the east the Ohura Fault was active and the uplifted eastern portion supplied sand and mud to the western lagoons. Paralic conditions developed adjacent to the fault and interbedded coal measures were deposited; but with new subsidence the transgressive seas allowed the upper Mokau sandstones and later the Mohakatino to overlap eastwards on to the Mahoenui Mudstone (Hay, 1967). Reportedly, rather common oil and gas indications were found, mainly in these upper Mokau sandstones in the old Prospect Road wells, drilled in 1928–30 north of Whangamomona (Watt, 1965). Gas analysed from Bore No. 1 of these wells contained 92·9% methane, and 1·8% ethane, besides 5·3% nitrogen (Ross, 1967, p. 45).

Possible source rocks are found in the Mahoenui Group with its thick mudstones, and in the Middle Mokau. A Mahoenui Mudstone sample from near Taumarunui yielded upon analysis 35·9% volatile hydrocarbons, while another mudstone sample from the Maryville Coal Measures (Middle Mokau) at the old Egmont Colliery, Tangarakau Gorge, produced in addition to 36·6% of volatile hydrocarbons a quantity of oil equivalent to 29·5 gallons per ton of mudstone (Elphick, 1959).

In the *Taranaki Basin* two formations have proven productive so far:

1. The Lower Pliocene Matemateaonga Formation in which the Moturoa Oilfield is located near New Plymouth, where drilling based on surface seepages had started as early as 1865. Nearly 50 wells have been drilled there over the years, and a cumulative production of some 200,000 barrels of oil and in excess of 65,000,000 cu ft of gas has been obtained (Lehner *et al.,* 1965). Most wells have produced from an interval 2,100–2,300 ft deep which contains several oil-bearing sands, and presently 3–4 wells are pumping a daily production of about 11 barrels of oil.
2. The Upper Eocene Kapuni Formation which in a faulted, anticlinal dome has formed a reservoir capable of producing 60 MM cu ft/d of gas and initially about 4,500 bbl/d of condensate (Watt, 1965); this reservoir lies between 10,500 and 12,000 ft below sea level.

The source of the oil is thought in both cases to be the Kapuni Formation, but little is actually known about conditions in the Moturoa field. There does not appear to be a real seal, and its production characteristics suggest a continued supply from deeper horizons, probably along fractures which have formed around the Sugar Loaf intrusions. These Pleistocene andesites at least seem to have controlled the growth and shape of the structure to some extent, while at the same time they could be responsible also for the subsequent escape of most of the original oil and gas content in older rocks.

Apart from the Matemateaonga Formation, potential reservoir rocks could possibly be found in the Mt Messenger, Mohakatino, and, particularly, the Mokau sandstones. The last named are undoubtedly the most prospective ones judged by their characteristics in surface outcrops. They are thick and partly massive-bedded, of fair to good porosity, and cover a comparatively large area. As with most other sandstones, however, their distribution and qualities are to a great extent governed by the general unrest of the area, with shifting shore lines and delta fans being built out at varied degrees from north-east and west-north-west, by changing sediment supply and varying velocity of subsidence. Particularly the deltaic character of such sandstones (cf. also the Kapuni Formation) suggests comparatively well pronounced boundaries between litho-facies, and the probably limited areal extent, subsurface, of sandstones of good reservoir qualities.

The Kapuni Formation, the oldest formation so far recognised in the basin, has proven productive in the Kapuni structure, while good oil and gas indications were actually encountered in most other places where this formation was drilled into. However, permeabilities are either not good enough, or structures not sufficiently closed; Mangahewa–1 drilled in 1960 produced gas and condensate on test, and although the gas contained less carbon dioxide than Kapuni, large quantities of water were also produced and the reservoir was therefore classed as non-commercial (Watt, 1965). Also in the Kapuni field, a top section of some thousand feet of the Kapuni Formation is tight, and much of the underlying formation is argillaceous sand and also unproductive. The fact that the reservoir itself is only part full, points to either an inadequate source or permeability barriers along the migration path, or perhaps later tilting which simultaneously increased closure but interrupted further migration (Watt, 1965).

As mentioned before, the Kapuni Formation here is considered a deltaic to lagoonal deposit, and the producing sands could possibly be tidal channel fills. As the Taranaki Fault was probably active during most of the time, the formation may thicken eastwards towards the fault-angle depression, but at the same time its reservoir qualities probably decrease due to more marshy conditions and deposition of clayey material. Coal seams and carbonaceous shales have been found intercalated in all sections of the Kapuni Formation, and these have by some authors been thought to be the primary source of the oil and gas (Rogers, 1964, 1965). Whether or not this is true is still a matter of speculation. While the world over, some oil is definitely known to have its origin in fresh water and terrestrial deposits (Hedberg, 1964), this is probably more often due to a parallel development with the formation of coal. Wherever abundance of organic matter exists—and this is a particularly common situation in transgressive, paralic environments in general—it depends on the conditions of deposition, preservation, and transformation of this organic matter whether it is converted, in the course of geologic time, into hydrocarbons in some cases and into coal in others (Fuloria, 1967).

It is probably safe to assume the oil and gas in the Kapuni Formation to have originated within this same formation; but instead of a source *in situ* by coal metamorphism, it is more likely according to Watt (1965) that it has migrated into the trap from a down-flank source in a more shaly, perhaps also marine facies. Deeper parts of the basin, and structures lying nearer the basin centre, would therefore be of particular interest; both source rock and reservoir characteristics are likely to improve below the southern Taranaki shelf. Tertiary sections perhaps up to 20,000 ft thick can be expected in western Cook Strait (Sprigg *et al.*, 1965), many of them marine, so that the up-dip portion towards Golden and Tasman Bay with the "Quartzose Coal Measures" at their base, which contain good sands, is also highly prospective.

West of the Wakamarama Fault, the Upper Cretaceous Pakawau Group of Cape Farewell Peninsula includes excellent sands, too, and comparable deposits further south along the West Coast are known to be oil-bearing (Young, 1967). It offers good prospects particularly along the shelf north of Cape Farewell, where an uplifted block with characteristics possibly very different from those in the Taranaki Basin proper, but not the less interesting, could extend to a considerable distance. Potential oil source and reservoir beds can be expected here to be present both in the Upper Cretaceous and the Lower Tertiary.

THE WEST COAST BASINS

General

Although Tertiary sedimentation extended south from Nelson and Golden Bay across most if not all of north-western South Island (Murchison, Westport, Greymouth, and south to Ross and further), corresponding sequences have been left intact only in minor, relatively isolated depressions and along fault wedges. Strong deformation and widespread erosion over much of the country have removed Tertiary sediments from most of the high-lying ranges, where they had formed a virtually continuous sedimentary cover deposited unconformably over a varied basement of Paleozoic and Mesozoic sedimentary and volcanic rocks, granites, and metamorphics. Potential oil basins, therefore, are mainly controlled by post-depositional, structural development. They are located on land around the Westport–Karamea area, the Murchison area, and the Greymouth area, and probably occupy much of the shelf also along most of the Westland coast.

In the Paparoa Range north of Greymouth, conditions when sedimentation started were similar to those in the Cape Farewell Peninsula further north. The Paparoa beds, however, are somewhat older and show an interval of time not represented in the Pakawau beds to the north. The Upper Cretaceous is represented by freshwater coal measures including siltstone, sandstone, and thick conglomerate, as well as brown, carbonaceous mudstone. This Paparoa Group is up to 2,600 ft thick in the southern central part of the Range, but thins rapidly east thereof, and also westwards towards the coast (Gage, 1949). Deposition was in an elongated, narrow trough which continued subsiding during the Lower Tertiary.

Wellman (1950) found intense leaching of the top Paparoa beds in the western part of the Paparoa Coalfield, and postulated an unconformity below the Lower Tertiary "Quartzose Coal Measures" or Brunner beds. Couper's palynological evidence (1960) indicated that the Paparoa Group is undoubtedly pre-Haumurian (but post-Ngaterian), thus basically Senonian in age. The overlying Eocene Brunner Coal Measures are up to 400 ft thick in this same area, and consist of highly quartzose grit and conglomerate, sandstone, and coal. While the Paparoa beds are restricted to the area around Greymouth, the Lower Tertiary Brunner freshwater beds have a much more widespread distribution, lying elsewhere unconformably on basement. The age of the Brunner Coal Measure is generally considered Upper Eocene, but the top of the formation at least, which grades into the lowermost marine beds, becomes gradually younger from south to north (Bortonian in the south to Duntroonian in the north, Suggate, 1950). Their thickness is highly variable over short distances, being typically from a few to several hundred feet, but exceptionally 1,000 ft as near Reefton on the east side of the Grey–Inangahua depression (Suggate, 1957). They may, however, be entirely absent due to non-deposition or erosion, as in several places near Murchison where marine Upper Eocene and also Oligocene beds transgress directly on to basement.

Upper Eocene marine beds (Kaiatan–Runangan) generally consist of massive, grey-brown, silty and micaceous mudstone of considerable thickness, but near Greymouth these are preceded by the 100–600-ft-thick marine Island Sandstone which there rests on coal measures. The overlying Kaiata Mudstone thickens eastwards from 1,700 to 5,000–6,000 ft near the axis of the present Paparoa anticline (Gage, 1952), east of which it thins rapidly again, being partly replaced there by the Omotumotu sandstone and conglomerate formation derived from an easterly source where basement was being eroded.

The Oligocene was a time of widespread limestone deposition. Port Elizabeth calcareous mudstone and Cobden marly limestone represent the typical development in the Greymouth area, having a combined maximum thickness of perhaps 1,700 ft. Locally, as near the Inangahua Junction, Oligocene rests practically on basement (is possibly separated from it by a few few feet of Eocene) and is itself only a few tens or hundreds of feet thick. Both the Eocene and Oligocene rapidly thicken from there to the Westport area on the coast, and at least the Oligocene also thickens to the east. These changes are reflected, too, by the marked sympathetic rank changes of Eocene coal, which is thought due to the change in overburden thickness (Suggate, 1959). In the Murchison area, the corresponding Matiri Formation is reported to be up to 9,500 ft thick (Fyfe, 1968), but this apparent thickness may partly result from repetitions through faulting. It generally forms high, conspicuous bluffs consisting of indurated, bluish grey marls and flaggy, arenaceous limestones.

The differential movements which had affected most parts of the region, particularly during the Upper Eocene, continued after the maximum transgression of Oligocene times; they caused pronounced changes in some of the depositional basins, leading to a rather greater diversity of Upper Tertiary sediments. After the Early Miocene, the Paparoa geosyncline began to rise in an incipient Paparoa Range (Wellman, 1948; Gage, 1949), while east thereof the Grey Valley geosyncline started to develop with comparatively strong subsidence, being filled with about 10,000–12,000 ft of Miocene, Pliocene, and Lower Pleistocene sediments (Dibble and Suggate, 1956). The marine Miocene and Pliocene Blue Bottom Formation is composed of clayey, blue sandstone and siltstone, glauconitic sandstone, shell-limestone, conglomerate, terrestrial sandstone, claystone, and lignite. While Miocene beds are present on the west side of this Grey–Inangahua depression, they are non-existent east of the Reefton area to the north of the Grey Valley, where white quartz sand, silt, and conglomerate with lignitic wood of Pliocene age rest unconformably on Upper Eocene to Oligocene beds (Suggate, 1957).

The Pliocene is followed conformably by Lower Pleistocene gravels (Old Man Group) which here are 5,000 ft thick. Further south, the Early Pleistocene sequence includes minor sand, silt, and lignite as well as glacial till and gravel. It is conformable with the Upper Tertiary, having been folded and eroded before Late Pleistocene glacial and fluviatile deposition (Bowen, 1967).

The Murchison Basin, which in Oligocene times had already experienced particularly strong subsidence, developed into the dominant feature during the Miocene and Pliocene when some 20,000–25,000 ft of sediments were deposited (Fyfe, 1968). Of these, the Mangles Formation, conformable or with only a minor disconformity over the Matiri Formation, accounts for 12,000 ft and is subdivided into a lower portion with mainly thin-bedded, alternating sandstones, siltstones, and mudstones, and an upper portion which consists of massive sandstone and local massive siltstone beds; the siltstones in the lower, alternating beds are all calcareous but the formation as a whole is basically non-calcareous. On the western side of the basin the Lower Mangles is, however, represented by thick sandstone beds with only minor, thin shale-silt partings. In contrast with the dirty, dense, and greenish grey Upper Mangles, this sandstone is quartz-rich and light grey, somewhat micaceous but rather well sorted, and clearly derived from the Victoria Range granite to the west. This facies is 4,500 ft thick along the Maruia River, and well exposed at the Maruia Falls; it seems to pass eastwards into the thin bedded sand-shale sequence typical of the Lower Mangles of the central basin, which is reported to include turbidites.

While the Mangles Formation is still marine, the Longford Formation which conformably overlies it is mainly terrestrial but does not include estuarine beds at its base. It is characteristically conglomeratic, with thick, massive conglomerate beds separated by sand-siltstone, and carbonaceous shale with some coal seams. The conglomerates are hard and well cemented with a sandy matrix. The pebbles are mainly greywacke, quartz, granite, sandstone, and mudstone. Leaf impressions and plant fragments are abundant in some of the shaly intercalations. The age of the formation is Upper Miocene in the Longford Syncline, while the beds in the Upper Maruia Syncline east of the Upper Maruia River, the younger of which contain schist-bearing conglomerates and therefore are correlated with the Old Man Group, are probably of Late Miocene to Early Pleistocene age (Bowen, 1964b).

Prospective Oil Formations

Oil and gas seepages are known from several places in the region, and a number of oil exploratory wells have been drilled, although unsuccessfully. Much subsurface information has also been obtained from hundreds of boreholes sunk for coal. In Pleistocene gravels at Kotuku, 15 miles southeast of Greymouth, the largest oil seepage in New Zealand is found, and had already led to a considerable number of wells being sited nearby in the early years of this century, between four and six of them having reached the basement (Morgan, 1911; Henderson, 1934, 1937).

The best reservoir rocks are undoubtedly found in the quartzose sandstones of the Upper Eocene Brunner Coal Measures. Although generally arkosic and somewhat micaceous, they are relatively clean and well sorted, with apparent porosities that can be rated as fair to good. Cement of varying amount is generally kaolinitic, sometimes quartzose, and rarely calcitic. Individual sandstone bodies can be up to several tens of feet thick, and are intercalated with carbonaceous shales and coal.

A similar description would apply to the sandstones of the Upper Cretaceous Paparoa Coal Measures, although in general they are less quartzose and less well sorted, thus of a somewhat inferior quality as potential reservoirs. They are nevertheless quite prospective, and in the course of coal mining activities the presence of petroleum and its widespread distribution in both the Upper Cretaceous and Lower Tertiary coal measures has become more and more evident throughout the Greymouth Coalfield (Morgan, 1911; Gage and Wellman, 1944; Gage, 1952; Young, 1967). However, the Paparoa Coal Measures are rather limited in extent as has been shown by the well log of Taramakau–1, drilled near the coast only 8 miles south-south-west of Greymouth, where Eocene beds rest directly on basement (McIntyre and Norris, 1966b).

The marine Island Sandstone above the coal measures is fine grained and dense, partly glauconitic and calcareous, so that its potential as a reservoir is probably not very great. Sandy members of the Kaiata Formation, on the other hand, and particularly sandstones of the Omotumotu Formation which replaces the mudstone to the east, contain fairly porous rock types; some dry gas and brackish water was found in the latter in the Kumara well (SFL–1, Lehner *et al.,* 1965). The Oligocene Cobden Limestone is in places quite porous, being a sandy to gritty, foraminiferal and glauconitic limestone of sugary appearance. Traces of oil are fairly common in this limestone on the crest of the Kumara dome (Watt, 1965); in the Marsden well (SFL–2, Lehner *et al.,* 1965), however, the limestone was found to be thin and non-porous, and without any trace of oil or gas, while in the Kawhaka well it is absent, possibly due to pre-Miocene erosion. The limestone shows good porosity in the Kotuku anticline, but contains only salt water under relatively high pressure. As the oil at Kotuku is contained in near-surface Pleistocene gravels, it has possibly seeped up along the fault which cuts across the dome, as suggested by Wellman (*in* Dibble and Suggate, 1956), while older formations would have been completely flooded. It may be derived originally from either this Cobden Limestone, or from Eocene beds more basinwards to the west.

Beds younger than Oligocene are generally dense, being mainly clay–silt as in the Blue Bottom Formation of the Greymouth area, or composed of tight and well cemented sandstone and conglomerate as near Murchison. Only the quartzose sandstone of the Lower Mangles Formation in the Maruia valley could be considered a potential oil formation among Upper Tertiary strata, but its structural situation is entirely unfavourable. The same can be said of the Longford conglomerates in the Upper Maruia syncline, on the north-western flank of which a line of oil seepages is reported near their contact with basement, which may be a normal overlap, or perhaps a fault (Fyfe, 1935).

Prospective formations, therefore, are basically restricted to the Lower Tertiary and Upper Cretaceous, and wherever the structural situation is favourable, efficient cap rocks are also present. However, the pronounced and rapid changes in litho-facies often make a regional assessment rather difficult, and this the more so as the complex tectonic history has affected oil migration patterns through time in a way not easily discernible. Perhaps this is the main problem of the region, and could explain why some of the best reservoir rocks in all New Zealand—and this in an area of plenty of oil indications—are just barren and dry, as for example the Brunner quartz sands on some good structures along the southern plunge of the main Brunner anticline. As this was a trough of long-lasting subsidence, oil may have been forced out of it and migrated up-dip before the Miocene uplift and erosion, and may therefore have been no longer available within the new drainage areas of subsequently formed anticlines.

Since many oil indications, seepages, etc., in the region occur in sandstones belonging to the basal coal measures far below the first marine beds, the most likely source of this oil should be looked for in the coal measures themselves. This would particularly be the case with the oil recently reported by Young (1967) from the Paparoa Group, which is of fairly widespread occurrence and generally contained in lensoid sandstones at the base of the Rewanui Formation, underlain by the Waiomo Mudstone. Dark brown or brown-grey silt-mudstone formations, in some localities up to 500 ft thick (Gage and Wellman, 1944), separate all four of the coal-bearing formations of the Paparoa Group, and carbonaceous shales are quite plentiful in both the Paparoa and Brunner beds. Apart from leaf impressions and other plant fragments, the Paparoa mudstones have yielded rare specimens of the freshwater mollusc *Hyridella* (Gage, 1952). They are therefore considered to be entirely of freshwater origin. Indigenous oil would thus be of a non-marine origin, but it is probably not necessary to advocate coal metamorphism for its generation as did Rogers (1965). In fact, oil shales associated with the coal measures have been reported by Morgan (1911) who gave the analyses of two samples with 45·63% and 33·37% volatile hydrocarbons, respectively; the latter sample, collected in the neighbourhood of a coal seam of the Brunner beds north of Blackball, yielded by distillation 22·7 gals/ton of oil and tar. A sample from Cobden (Elphick, 1959) had 27·5% volatile hydrocarbons, and oil was obtained at 11·6 gals/ton*.

Lower Tertiary marine beds, particularly the Kaiata Mudstone, have often been referred to as possible source rocks for petroleum. However, while their dark colour, pyrite concretions, and sparseness of fossils perhaps indicates a suitable facies, the actual amount and type of organic matter in these mainly fine-silty and micaceous deposits are unknown and probably not everywhere as great as has been thought. Their great thickness and widespread occurrence, on the other hand, are certainly a positive factor. Probably, therefore, both the Upper Eocene mudstones and Oligocene shaly limestones and marls should be considered as a possible source. Particularly in the Murchison area, where coal measures are much less developed, they are likely to be of considerable importance in this respect, being extremely thick in places, and more like bituminous shales than elsewhere. According to Fyfe (1928, 1968) both the Maruia and Matiri mudstones and marly shales, throughout sequences of many thousands of feet, "smell strongly of oil on fresh fracturing".

No rocks younger than Oligocene can be regarded as a possible source for petroleum in the West Coast region.

THE EAST COAST BASIN (NORTH ISLAND AND NORTH-EAST MARLBOROUGH)

This potential petroleum basin extends all along the east coast of North Island, where it covers a belt about 50 miles wide and 300 miles long, i.e., a total area of some 15,000 sq miles. It is bordered in the west by the basement outcrop of the "Main Range", which consists of Permian to Jurassic sediments; this greywacke suite is severely distorted and folded, highly indurated, and somewhat metamorphosed. To the extreme south, in southern Hawke's Bay and Wairarapa, Jurassic to Lower Cretaceous basement slices are exposed east of the "Main Range".

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*According to Dr R. P. Suggate (N.Z. Geological Survey), pers. comm., these samples are probably not oil shales, but high-ash canneloid coals.

Prospective formations are present within a thick Upper Cretaceous to Tertiary sequence, which is entirely marine and basically continuous, and reflects a pattern very different from all the basins along the west coast of New Zealand. The geological history is very complex; local unconformities, deleting stages and series, and rapid facies changes over short distances are very common. On the other hand, sequences of monotonous lithology often span several stages. Such handicaps to lithologic subdivision are so pronounced that most geological mapping, particularly in the northern area, has been practical only on a time-stratigraphic basis, i.e., with the help of fossils.

No unambiguous, convincing interpretation has yet been offered of the tectonics of the East Coast Basin. Analysis and interpretation of the tectonic evolution are complicated by: (*a*) the great variety of interfering structures, (*b*) unusual structural conditions and features such as piercement domes and clay diapirs which are possibly related to basement wrench fault tectonics (Kingma, 1958c; Ridd, 1964), (*c*) growth structures which developed slowly through long periods of time contemporaneously with deposition, and (*d*) the possible occurrence of large-scale gravitational slumping which locally may have contributed to the complexities of the area (Stoneley, 1962).

Indications of the presence of petroleum are numerous: good oil seepages, gas emanations, mud volcanoes, salt water and hot springs, and oil-stained and oil-smelling rocks are of widespread occurrence. Oil seepages are particularly common in the East Cape region north-east of Gisborne, where Maori inhabitants knew of oil before European settlement, and active exploratory engagements by the new immigrants began as early as 1874 (Adams, 1910; Henderson and Ongley, 1920; Clapp, 1926; Ongley and MacPherson, 1928). Since 1926, 11 wildcat wells have been drilled in the general Gisborne area, but so far only one, Opoutama-1 drilled to 12,000 ft in 1967, has gone well below the base of the Tertiary to test a thick Upper Cretaceous sequence. Structural and drilling difficulties, the latter mainly due to steep subsurface dips encountered and the plastic behaviour of a thick Eocene bentonite sequence, prevented deep-drilling in the past. This is now no problem, provided drilling is conducted carefully and on appropriate locations.

Stratigraphy

In Late Jurassic to Early Cretaceous time a major diastrophic cycle, the Rangitata orogeny (Kingma, 1959; post-Hokonui orogeny of Wellman, 1950) concluded the geological history of the New Zealand Geosyncline. Subsequently, the deposition of Cretaceous and Tertiary rocks was largely restricted to basins and troughs of a more local character and limited extent. Of these, the East Coast Geosyncline, which extends along the east coast of the North Island and into the north-eastern part of the South Island, is the largest. Intermittently and particularly in its early history, it received sediments both from the west and the east (Kingma, 1960). Internal differentiation into tectonically controlled basins of particularly deep and rapid subsidence, and constantly changing dimensions related to the increasing tempo of overall deformation, controlled local deposition patterns of great complexity. These, however, have been worked out only to a very limited degree.

In the East Cape region, the Cretaceous sequence is exposed mainly in the Raukumara Range, but Cretaceous sediments also outcrop in the striking Te Puia domal structures south of Ruatoria, to within a few miles of the east coast (Kingma, 1965). An account of stratigraphic relations has been given by Wellman (1959) who, mainly on the basis of sequences of *Inoceramus* species, divided the sequence into four series and 12 stages. All of this Cretaceous is represented by a sand-shale facies, but apparently much lateral variation occurs within the area. According to Wellman, the Clarence Series (Albian to Cenomanian), and more markedly the Raukumara Series (Turonian–Senonian), grade southward from redeposited alternating silt-sandstone beds to massive shelf sandstone. Wellman also considered that a more pronounced change of facies would occur at right angles to the geosynclinal axis.

Complex lithofacies variations apparently occur in the Taitai Series which underlies the Clarence Series; although outcropping at widely scattered localities, a general scarcity of fossils and incomplete sections in structurally complicated positions have made it difficult to document the sequences. At Mount Taitai, in the Tapuaeroa valley, the massive but unfossiliferous Taitai sandstones, grits, and conglomerates are underlain by dark, crushed mudstone which is Wellman's type Mokoiwian Stage, the lower of the two stages comprising the Taitai Series. The Mokoiwian is thought by Wellman (1959) to be the oldest of the Cretaceous stages and would correlate approximately with the Aptian. Whereas Macpherson (1946) postulated a thrust-plane at the base of the Taitai Sandstone, Wellman considered the sequence to be normal and continuous. Yet it remains uncertain if the Taitai Sandstone really belongs to the Korangan Stage, the higher of the two Taitai Series' stages, which has its type locality at Koranga about 60 miles south-west of Mt Taitai. The type Koranga Sandstone is lithologically different and consists of massive, muddy, and fine-grained sandstone, locally laminated, containing scattered lenses and pockets of pebbly mudstone and intraformational breccia. It grades into and is overlain conformably by sediments of the Urutawan Stage (Clarence Series), but its base has not hitherto been considered to be exposed. However, the field relationships and a basal conglomerate indicate that the type Korangan Sandstone is probably separated from the underlying, distinctive thin-bedded greywackes by an angular unconformity (I. G. Speden, pers. comm.; and personal observation). At Koranga Falls, just over a mile to the west, the Urutawan sediments rest directly on the older greywacke rocks with a sharp and clear-cut angular unconformity of some 80°. The nearly flat-lying Urutawan at this locality is composed of an alternating mudstone-sandstone sequence with thick and massive, partly conglomeratic sandstones at the base, grading upwards into thinner-bedded mudstones with intercalated, poorly sorted grits and flaggy, grey-green sandstones; these are all dense and dirty. Thin conglomeratic lenses are particularly fossiliferous, and abundant carbonaceous material (plant remains including leaf imprints) are found in several horizons.

Both the sedimentary characteristics and faunal content suggest that the Koranga Sandstone at its type locality could represent a local lenticular body below the Urutawan, or perhaps a different facies development within the lower portion of the Urutawan (I. G. Speden, pers. comm.). Because of the lack of diagnostic fossils in the Taitai Sandstone in the Tapuaeroa valley region, apparent lithological differences between the so-called "Taitai Series" sandstone units at Koranga and in the Tapuaeroa valley, and the consequent uncertainty of correlation between the Koranga and Taitai sandstone units, the concept of the Taitai Series and the position of the Mokoiwian Stage remain rather uncertain. Likewise, the question of whether or not the Lower Cretaceous, i.e., in particular the Neocomian, is present, or how much of it is present, and the problem of tectonic evolution in earlier Cretaceous time remain to be answered. Undoubtedly the unconformity at Koranga Falls is of stratigraphic importance, and the mapping of extensive areas as undifferentiated Taitai which may comprise largely unfossiliferous rocks on either side of an unconformity (e.g., Kingma, 1965), can hardly be warranted. More work is required, especially as no pre-Aptian Lower Cretaceous fauna is known in the East Cape region (or anywhere else in New Zealand), and the nearest stratigraphically older fauna is one of Puaroan age (Upper Jurassic) in the Raungaehe Range, Bay of Plenty (Stevens, 1963). On the other hand, there is a continuous sequence known from about Aptian–Albian upwards, which also suggests that the apparent gap in the geological record is a real one representing major events.

This field of research is particularly important, especially as the Mokoiwian Mudstone and the Taitai Sandstone, as developed in their type locality, are some of the more attractive formations from the oil geologist's point of view. Wellman (1959) has noted the high organic content in the originally dark mud of the Mokoiwian, while Pick (1962) emphasises the many hydrocarbon indications, gas emanations, and traces of solid residues found in these beds, and Ongley and MacPherson (1928) noted the distinct oil smell characteristic of the mudstones, which have a thickness of several thousand feet. As there are lateral facies changes into lenticular sandstone bodies—and the massive Taitai Sandstone itself is regarded by Pick as one of those, which would be of deltaic origin—the possibility remains of a potential reservoir build-up in close relation with the source Mokoiwian dark shales.

The Upper Cretaceous Clarence, Raukumara, and Mata Series have a combined thickness of some 15,000 ft (Kingma, 1965), but here again, there is much lateral and vertical facies variation. North-west of Hawke Bay, successively younger formations unconformably transgress over steeply folded sediments (largely undated by fossils but attributed to Jurassic to (?)Lower Cretaceous) and appear to thicken eastwards away from the ranges (Grindley, 1960).

The most characteristic sedimentary development is a thin and rhythmically bedded, alternating sand-silt-mudstone sequence which often represents a typical flysch facies (Kingma, 1965). More massive, though generally dense sandstones occur intercalated in the Raukumara Series, while the Mata Series (Piripauan and Haumurian Stages, Campanian–Maestrichtian) are mainly represented by the so-called Whangai shale facies (Lillie, 1953). This is a rhyolitic, tuffaceous mudstone, more or less strongly silicified, often of a creamy colour. In the Lower to Middle Haumurian, however, thick quartz sands, grits and conglomerates and some greensands, are very characteristic in several areas (the "Tahora sandstones" of Jablonski, 1934), and have by many been considered a potential reservoir rock of good quality. According to Pick (1962), these sandstones are most commonly clean and well sorted, and "smell faintly to strongly of oil when broken". Their porosities range up to 28%, and permeability to 138 md. As their thickness may be several hundred to well over a thousand feet, they are certainly one of the best prospects on the east coast. However, their distribution is irregular, and both thickness and lithology vary, while in places they may even be entirely absent.

South of Raukumara Peninsula is the depression of Hawke Bay, where Tertiary sediments reach far inland and directly overlap the greywackes of the Main Range; no Cretaceous sediments are exposed here for a considerable distance. Still farther south, structural conditions change profoundly, and where the Cretaceous is exposed in Southern Hawke's Bay and Wairarapa it occurs in elongated, upthrust slices and, along the east coast, in the cores of narrow, faulted anticlines. This belt is separated from the older formations of the Main Range to the west by a series of Tertiary basins (Lillie, 1953; Heuvel, 1960; Kingma, 1962, 1967). Here, also, the position and relations of so-called Taitai Series rocks are poorly known, but a 200–300-ft-thick conglomerate of Motuan age (Albian) suggests a major environmental change, which initiated the Upper Cretaceous to Tertiary cycle of sedimentation (Kingma, 1967). Most of the sequence is made up of thin-bedded, alternating sandstones, siltstones, and mudstones; thin intercalated limestones and concretionary siltstones are locally quite common. The occurrence of spilitic lavas and conglomerates with abundant pebbles of volcanic and acid plutonic rocks thoughout the Upper Cretaceous may be typical of this southern region. The Mata Series, especially the Haumurian Stage, is again characterised by the Whangai shales, which are composed of thick siliceous tuff, flint, and limestone beds.

In the north-eastern part of the South Island, in Marlborough and the Kaikoura Ranges (Lensen, 1962), the complex facies and thickness variations in the Upper Cretaceous sequences depict a complicated pattern of regression and transgression and local diastrophic movements. Unconformities occur in some places, but deposition may have been continuous from Hokonui through to the Clarence Series in other areas (Suggate, 1958). Local terrestrial conditions, represented by quartzose coal measures in both the Ngaterian and Piripauan Stages, reflect the particular location of the area which is transitional between the two major provinces of the East Coast geosyncline and Canterbury. In general, however, the typical development of most of the Clarence and Raukumara Series is an alternating sequence of graded bedded siltstone-mudstones with some concretionary sandstone and conglomerate intercalations. The Mata Series is mainly composed of glauconitic sandstone and concretionary mudstone, passing upwards into regularly bedded flint and sulphur-stained argillite with limestone lenses similar to the Whangai facies of the North Island. These, in turn, grade into the conspicuous, siliceous limestone of the lowermost Tertiary.

Uninterrupted, marine sedimentation from Cretaceous into Tertiary times is the characteristic feature of the East Coast geosyncline. It has been postulated that at the beginning of the Tertiary, the geosyncline lay between a still-persistent structural high to the east, and the New Zealand Geanticline to the west (Kingma, 1960). The eastern high soon ceased to be of importance, while the western Geanticline was not a major sediment-producing area until the Upper Tertiary. Extensive deposition of fine material, greensand, mud, and calcareous ooze rich in Foraminifera was the result of this rather stable and quiet phase of the geologic history (Fleming, 1962). However, sedimentary structures indicate the occurrence of local tectonic unrest during this period also (Waterhouse and Bradley, 1957). Thick mudstones, which transformed into montmorillonitic clays, loosely called bentonites, are of widespread occurrence and one of the conspicuous sedimentary features of the east coast Paleocene and Eocene.

A major change in sedimentation occurred near the end of the Oligocene (Kingma, 1960; Ridd, 1964). This is indicated by the absence of Pareora Series (Lower Miocene) beds in certain areas and an influx of coarse sediment derived from the west. Similar sediments continued to be typical for most of the Upper Tertiary. At the same time, increasing tectonic deformation within the geosyncline caused complex lithological patterns and rapidly changing thicknesses (Kingma, 1957b, 1958c, 1960; Ridd, 1967). Miocene flysch-type successions in strongly subsiding basins contrast with massive sand-siltstones in nearby, relatively stable shelf areas (Kingma, 1958a). The total thickness of the Miocene may be locally up to 30,000 ft (Kingma, 1964). Folding of strata and upheaval of blocks along faults while deposition continued, led to an even more localised pattern of sedimentation. In general, the Pliocene saw shallower seas with the development of islands and shoals and apparently strong tidal currents, which winnowed the sediments (Kingma, 1957a, 1958b). Pliocene beds almost entirely lack the flysch-type alternating facies of the Miocene and are characterised by widespread coquina limestones at certain horizons. In the Hawke Bay depression, the thickness of the Pliocene is 13,000 ft followed by another 7,000 ft of Lower Pleistocene (Nukumaruan) sandy silt and conglomerate with abundant shell beds and pebbly limestone (Grindley, 1960).

Southwards along the western margin of the basin, Upper Tertiary sediments successively overlap further on to the basement greywackes of the Main Range. Transgression continued until, during the Pliocene, the seas covered the range completely to connect with the Wanganui Basin. In the south-east corner of the North Island, Miocene and even Pliocene beds rest unconformably on older formations. Here there is a marked break at the base of the Miocene (Wellman, 1954; Kingma, 1967). Corresponding movements are more pronounced still further south, in the north-east of the South Island, where the extremely thick "Great Marlborough Conglomerate", of Middle to Upper Miocene age, has accumulated around the nose of uprising mountains and in fault angle depressions (Lensen, 1962). Here, also, marine sedimentation continued well into the Pliocene, at least in local depressions, but the overall pattern is one of a regional regression related to the Kaikoura Orogeny (Kingma, 1959), which commenced first in the south and gradually extended northwards.

Prospective Formations

As already stated, the oldest formations with any prospects occur in the so-called Taitai Series. However, this refers only to the lithotypes of the type locality at Mt Taitai (Mokoiwian Mudstone as potential source rock, and Taitai Sandstone, if well developed, as reservoir), whose exact stratigraphic position and relation are still uncertain. Much of what has been mapped as "Taitai Series" (Kingma, 1965, 1967; Grindley, 1960) is, in fact, highly indurated greywacke of doubtful age, and has to be regarded as effective basement.

Whether or not Taitai sandstones have any appreciable subsurface extension is still a matter of speculation; nowhere have they been reached by the drill. Also, their quality is questionable, as they appear rather dirty and tight in exposed sections. However, they represent the nearest to a potential reservoir build-up, and their facies relationships suggest that possible improvements in porosity might occur in certain areas.

Most of the Upper Cretaceous sequence is composed of dense and fine-grained, alternating mud-siltstones which in many places resemble flysch-type successions with all their characteristic sedimentary features, slump structures, graded bedding, etc. Good storage rocks are mostly absent, but many of the mudstones and carbonaceous shales which occur in considerable thickness throughout the sequence are reported to emanate a distinct oil smell, while occasional porous beds like greensands, etc., almost always contain traces of oil or give off some gas (Ongley and MacPherson, 1928; Lillie, 1953). According to Lillie (1953, p. 32) Maestrichtian Tapuwaeroa beds would be the most likely source of petroleum in the Dannevirke area (south of Hawke's Bay), where oil smells and occasional seepages have been noted in these rocks. Picks' (1962) investigation of the black carbonaceous shales of the same age north of Gisborne, however, suggests that these "oil shales" really contain kerogen which is insoluble in petroleum solvents. Therefore these sediments would not qualify as source beds. Nor are they likely to be rich in bituminous matter, as the destructive distillation of a composite sample gave an oil yield of not more than 1·8 gals/ton (Ongley and MacPherson, 1928, p. 64).

No doubt the many seepages prove that free hydrocarbons do occur in at least some of the Upper Cretaceous shales. There is, on the other hand, less certainty about the presence of potential storage rocks. Apart from the possibility that locally the Taitai Sandstone might offer, only the Lower to Middle Haumurian (Maestrichtian) sandstones appear to be capable of forming a reservoir. They look quite promising in certain sections (Pick, 1962), but, as mentioned before, the question of their geographic persistence and distribution is unresolved. Reservoirs formed by fractured and shattered but otherwise tight rocks could be possible in certain cases; the particular conditions associated with cross-faulting and piercement structures, as they occur in some areas, would seem to enhance this possibility.

Any Cretaceous reservoir would find an extremely good seal in the thick mudstone and bentonite of the Lower Tertiary and only faults might permit the escape of hydrocarbons. Almost all seepages are in fact related to fault zones and piercement structures, but the nature of highly mobile bentonite would probably impede the easy passage of oil and gas in most cases.

The Tertiary sequence probably is less likely to contribute to possible oil or gas generation—the exception being some of the lowermost, chocolate and black shales as those at Waipawa (Hornibrook and Harrington, 1957; Lehner *et al.,* 1965), the development of which is intimately related, however, to the preceding Cretaceous succession. Higher up no particular source rocks appear to be present, while potential storage rocks, for reasons given above, will not easily become filled with Cretaceous oil. Locally, however, traces of oil and gas are known in Tertiary areas, but as a rule the porosity of Tertiary sandstones is not very high. They are usually muddy and dirty, or have a calcareous or siliceous matrix. Tectonic unrest and the rapidly changing pattern of depositional trends appear to have been unfavourable for the formation of suitable reservoir bodies. Only in the Middle and Upper Miocene, and particularly in the basal Southland Series, are there local massive and thick-bedded shelf sandstones; but here also, porosities in subsurface samples are reportedly not as good as in surface outcrops, which evidently have been subject to considerable weathering and leaching.

In south-east Wellington and northern Marlborough, where pre-Miocene erosion has brought various Cretaceous formations into unconformable contact with overlying Miocene basal sandstone and conglomerate, conditions may have been created that were suitable for local accumulations of Cretaceous oil or gas in Miocene traps. This mechanism is particularly suggested in northern Marlborough, where an active oil seepage from shattered greywackes near a fault contact with Upper Tertiary sediments has been known for a long time (Morgan, 1921), and to the south-west of which several oil and gas seepages have since been found in the area of exposed Cretaceous rocks (Lensen, 1962, and pers. comm.). This supports the idea that pre-Tertiary rocks indeed are the source of any petroleum present.

Plio-Pleistocene beds, mainly because of their structural situation and lack of cover, in general do not appear suitable for building up any appreciable reservoir. Some lithologies, however, show good porosities; particularly the Waitotaran limestones (calcarenites) in the Hawke's Bay area would certainly include potential storage rocks, provided there are suitable permeability barriers. Prospects are enhanced by their great thickness, but more detailed studies are needed in this respect.

THE CANTERBURY BASIN

Extending for about 200 miles along the central east coast of the South Island, this basin is in direct continuation from the East Coast Basin of North Island and Marlborough. However, sedimentary conditions profoundly changed at about the southern edge of the present-day Kaikoura Ranges; to the south the tectonic evolution followed entirely different lines, and the structural unit of the Canterbury Basin therefore exhibits a picture which is different in every respect.

Because much of the Tertiary cover along the western margin has been removed by erosion due to regional uplift (Speight, 1915; Grindley, 1951; Wilson, 1956), the actual basin appears considerably reduced in size but is still about 30 miles wide on land just south of Christchurch; no off-shore limit is known to the east, where the continental shelf covers some of the widest areas around New Zealand coasts (Brodie, 1964). In the same area south of Christchurch, it is 70 miles out to the 100 fathom line, which possibly gives a measure to the total width of the basin. Little, however, is known about subsurface basement structure and topography. On land the depth may be up to about 7,000 ft as suggested by gravity (Hatherton, 1952), but locally much shallower basement highs can be expected; on Banks Peninsula, greywacke basement and mid-Tertiary sandstones appear above sea level underneath an extensive cover of young volcanic rock (Oborn and Suggate, 1959).

As seen around the landward basin margin, the basement consists of folded Triassic–Jurassic greywacke and argillite, including basic volcanics, and locally of rhyolitic and andesitic complexes as well as syenitic to gabbroic intrusives (Speight, 1928; Mason, 1948; Gregg, 1964). After long denudation with much chemical weathering, the sea started to invade the area from the east in the Cretaceous, reaching the inner margin of the Canterbury Plains in Maestrichtian time. At the base of the marine deposits, freshwater coal measures are found in many places. Their thickness varies widely, and is commonly a few tens or hundreds of feet. In the Malvern Hills west of Christchurch, however, it is undoubtedly much greater, but may not reach the 5,000 ft reported by Speight (1928). Depending on their location with respect to the encroaching sea, their age is Campanian to Maestrichtian (Couper, 1960; Wilson, 1963) or, as occurs furthest west and south, lowermost Tertiary (Allan, 1927; Marwick, 1935; Speight, 1938; Wellman, 1953; Wilson, 1953; Suggate and Wilson, 1958). Regardless of the age of the transgression, the sedimentary succession as a whole, both in the coal measures and the marine beds above, is very much the same thoughout the area, indicating comparatively slow subsidence and rather uniform conditions. The freshwater beds generally consist of carbonaceous silt and mudstone with some lignitic coal seams, locally including greywacke-quartz conglomerate at the base. Both clay deposits and—particularly in the upper portions—very clean quartz sand are widespread and characteristic features.

The marine deposits as a whole are still very quartz-rich, but generally finer, calcareous and silty-muddy, and becoming increasingly glauconitic upwards. They pass into clayey mudstone, and this in turn into marl and limestone. Locally, basaltic and andesitic lavas and tuffs are found resulting from submarine eruptions in Late Eocene to Oligocene time, while shallow sills and dikes were also emplaced into still wet and uncompacted sediments (Gage, 1957; Speight, 1928, 1938). By the Late Oligocene, the transgression had reached its maximum exent. A total thickness of sediments, up to this stage, of approximately 1,200–1,500 ft has been measured both to the north and south of the Canterbury Plains (Wilson, 1963; Wellman, 1953). A general thickening towards the east can reasonably be assumed, but no definite figures are available.

In the Lower to Middle Miocene, uplift occurred to the west and a long-lasting cycle of intermittent regression began. Deposition of muddy silt and sandstone with some calcareous shell beds were the result. Non-marine beds were deposited in the extreme south unconformably over older formations, probably as early as the Upper Miocene (Gage, 1957). In the north, warping occurred in the still sea-covered areas. Non-deposition in the Middle and Upper Miocene in some areas, and the unconformable character of near-shore shell conglomerates in the Pliocene (Gregg, 1959) are clear signs of the approaching end of the marine domain: at an increasingly greater rate of deposition, the sediments grade upwards into Lower Pleistocene freshwater gravel and sand. The thickness of the sequence younger than Oligocene is probably more variable, and is perhaps of the order of 4,000 to over 5,000 ft (Gregg, 1959; Wilson, 1963). The picture of the later history from Pleistocene to Recent times, finally, is greatly complicated by fluctuating sea level and changes of load of the various rivers from the rising mountains in the west, by aggradation and downcutting combined with further warping and folding.

Reviewing this sedimentary sequence with respect to the possible occurrence of petroleum source material, it appears that the marine members mainly composed of detrital silt and clay are not very suitable, as they contain little if any organic material. Nor have the extensive Oligocene limestones any source bed characteristics; the Amberley Limestone is basically a marly *Globigerina* ooze, whitish and chalky, while the overlying Weka Pass Stone, which is separated by a minor diastem from the Amberley Limestone, is massive and cream-coloured, somewhat coarser in texture and slightly arenaceous-glauconitic. However, the presence of some organic matter in an originally reducing environment is suggested for part of the Cretaceous portion, which not only is rich in glauconite but in particular is characterised, according to Thomson (1920), by widely distributed iron sulphide ("sulphur sands" and "sulphur mudstone", p. 343). As a result of subsequent oxidation, ferrous sulphate and a small portion of free sulphur is reported to occur in these beds which are commonly characterised by their yellowish efflorescence.

Carbonaceous shale and siltstone have been reported from nearly all the known sections where the freshwater coal measures occur at the base of the marine sequence. Although not really attractive for both lithology and particularly their limited thickness, these beds would constitute the only other possible source for hydrocarbons, which thus appears entirely restricted to the uppermost Cretaceous.

Hydrocarbon traces have been mentioned, in addition, from Upper Jurassic basement rocks in northern Canterbury. On the east side of the Cheviot Hills, such rocks "emit a strong ephemeral kerosene-like odour when freshly broken or crushed" (Fleming, 1958, p. 388). When heated, a sample produced a small amount of gas which included traces of both saturated and unsaturated hydrocarbons. A high methane content, and in one sample as much as 13·2% ethane, have been obtained from the hot springs at Hanmer (Ross, 1967) which are located on a branch of the Hope Fault, in terrain entirely surrounded by similar basement rocks (Gregg, 1964). Although the induration, incipient metamorphism, and excessive structural deformation of these rocks are such as to exclude them from being a potential oil formation, it is probable that conditions favourable to the generation of oil and gas existed in parts of the area also in the Jurassic. Much, however, will have been destroyed or will have escaped as a consequence of the Rangitata Orogeny and the long subsequent period of denudation and erosion. Nevertheless, some free hydrocarbons still are available (particularly from highly fractured areas), and more could perhaps have been trapped in suitable reservoirs of the unconformably overlying Cretaceous to Tertiary cover.

Potential storage rocks in this younger sequence are rather rare, however. Sandstones are fine-grained to silty, and clayey, all somewhat micaceous, and generally tight; the limestones are dense, but the oyster bed at the base of the marine sequence in the Waipara River and surroundings (northern Canterbury) is reported to be highly porous (Wilson, 1963). At the Waipara River it is about 20 ft thick and consists of two to three shell beds with sandy intercalations; apparently it has a marked smell of petroleum (Thomson, 1920, p. 343). The freshwater beds underneath are only about 40–50 ft thick in this section, and consist of thin-bedded, dirty sandstones and carbonaceous siltstones. Above the oyster bed, fine-grained but very clean, whitish quartz sand follows in a rather massive sequence of about 100 ft, exposing only weak bedding and minor breaks of carbonaceous silt-shale. Upwards it gradually passes into more argillaceous and glauconitic silt to fine sand with ball-like concretions containing Saurian remains. These Saurian beds and the overlying Waipara Greensand (Thomson, 1920), which consists of fine-grained, thin-bedded glauconitic sandstone alternating with silty mudstone, are of Maestrichtian to Danian age and are conformably overlain by Paleocene to Eocene "bentonite" or grey, partly glauconitic and marly, fissile clay.

Undoubtedly the deposit with the highest porosity and best potential reservoir qualities is the pure quartz sand that is found in several sections at the top of the coal measures. Some of the sand has been quarried for moulding and glass manufacturing (Speight, 1938). Quite commonly it is almost entirely composed of quartz grains, with but a small amount of iron-staining. Lacking any cement, the sand is generally loose and massive with only a faint indication of bedding; the thickness may be up to several tens of feet. Near Hart's quarry in the Malvern Hills, white quartz sand has been reported by Speight (1928) to be 300 ft thick, overlain by slightly glauconitic, calcareous sandstone and shell beds. The sand here is fine to medium grained, in small streaks also coarse grained; a porosity of 40% was mentioned by Speight (p. 67). From other places, gritty and pebbly portions have been reported.

The origin and conditions of sedimentation of this quartz sand are insufficiently understood, and thus its paleogeographic distribution is entirely a matter of speculation. It is definitely related, however, to a particular tectonic and environmental setting along the margin of a transgressive sea, and is certainly derived from a mature land surface which had undergone long and deep weathering; repeated selective processes like constant reworking by continuously shifting streams, prolonged wind and wave action, and longshore and estuarine tidal currents perhaps intervened in their formation. While rhyolitic land surfaces apparently furnished a large proportion of the quartzose sediments deposited in certain coal measure areas, e.g., Malvern Hills, the occurrence of conglomerates with rhyolitic pebbles overlying greywacke basement suggests a rather complex pattern of current directions, including transport of sediment perhaps originally derived from an easterly source (Speight, 1928). It appears reasonable, therefore, not to assume *a priori* a large lateral eastward extent of this particular type of deposit.

The age of this quartz sand, then, wherever it occurs, is immediately preceding the marine transgression; the deposit may in places also have been reworked by it, probably in an environment of subsiding coastal flats.

THE SOUTHLAND BASIN

General Geology

Controlled by a peculiar tectonic setting, the southernmost of young sedimentary basins in New Zealand extends north of the south coast of South Island. Subdivided into two smaller basins by basement highs of Upper Paleozoic basic igneous complexes (Takitimu and Longwood Ranges), the Southland Basin occupies a southward-opening wedge situated between the south- to south-east-trending Southland Syncline of Permian to Jurassic rocks and the south-west-trending Fiordland complex composed of older Paleozoic, metamorphic and igneous rocks.

Originally, however, the Tertiary transgression covered a much wider area including most if not all of Fiordland and Southland, and parts of western Otago. Subsequent differential movements caused extensive erosion and stripping; the preservation of Lower Tertiary sediments, as well as continued sedimentation through the later Tertiary and Quaternary has been restricted to the two smaller basins mentioned above. Apart from many local depressions and fault angle wedges which are of no direct bearing for the purpose of this study, these are:

(*a*) The Waiau – Te Anau Basin in the west, and (*b*) the Southland Basin proper towards the east-south-east, here termed Invercargill Basin. The prospective basins are thus very limited in size, about 20 × 30 miles for the latter, and roughly 20 × 80 miles for the Waiau – Te Anau Basin.

In the western of the two basins, the basement probably consists exclusively of Paleozoic metamorphic and igneous rocks. In the Invercargill Basin further east, however, much of the basement is made up of Permian to Jurassic sediments. These are mainly of the greywacke type, including much tuffaceous greywacke and vitric tuff, mudstone, arkosic, and greywacke sandstone, granitic conglomerate, etc. (Wood, 1956). Their lithology is probably nowhere favourable for the generation and/or storage of oil, and since they also have suffered strong induration, their classification as effective basement can hardly be disputed. They were deformed into shallow folds during the post-Hokonui orogeny, and eroded and peneplained before the Lower Tertiary transgression.

In restricted basins (of unknown extension, however), terrestrial sedimentation had already begun during the Upper Cretaceous (Couper, 1960; Bowen, 1964a), but the only known deposits of this kind that have resisted subsequent erosion are found in the Ohai Coalfield located in a west-north-west trending, downthrown graben (Wood, 1966b). These coal measures of Campanian to Maestrichtian age, the Ohai Group, are about 1,000 ft thick; but, as a result of widespread erosion before the deposition of the overlying Eocene coal measures, the original total thickness is not known; nor is it possible to ascertain their original distribution, or present subsurface extent.

Lithologically the Ohai Group ranges from clay and carbonaceous mudstone to conglomerate, and includes coal seams in the basal Wairio Formation and particularly in the Morley Coal Measures at the top of the group. Coarse quartz grit and white quartzose sandstones are reported from the intermediate New Brighton Conglomerate, while sandstone is said to form the predominant lithology of the overlying Morley Coal Measures (Bowen, 1964a). It is mostly white and composed mainly of quartz and altered feldspar, and micas; bedding is generally massive, and while finer sandstone always is rather clayey, the coarser grades appear to contain little clay.

The Upper Cretaceous Ohai Group is unconformably overlain by Upper Eocene to Oligocene coal measures and marine siltstones and mudstones. In the area of the Ohai Coalfield, Upper Eocene Beaumont Coal Measures rest on various formations of the Ohai Group as well as on basement rocks. They are typical fine-grained coal measures with predominant mudstone, siltstone, and shale and impersistent coal seams; they are 500–600 ft thick and are followed by freshwater sandy mudstones and siltstones with bands of ferruginous nodules. These pass upwards into marine beds of Oligocene age.

Everywhere else in Southland, basement rocks are directly overlain by a similar sequence of Eocene–Oligocene coal measures and marine beds, mainly mudstones. Particularly in the west, this Lower Tertiary attains great thicknesses. At the northern end of Lake Te Anau and at the Hump Ridge north-west of Te Waewae Bay, the terrestrial beds alone are several thousand feet thick (Grindley, 1958; Wood, 1966a, in press). However, great and rapid variations are present as is shown by the sandstone sequence only 300 ft thick underlying Oligocene marine limestone between South and Middle Fiords, western side of Lake Te Anau (McKellar, 1956).

The main lithologies of the Lower Tertiary terrestrial beds are hard, thick-bedded sandstones, mainly arkosic, conglomerates and flaggy, often carbonaceous siltstones; they include plant and coalified wood fragments and occasional coal seams. Near Orepuki south-east of Te Waewae Bay, 8 in. of oil shale is found within such coal apart from several thinner seams. The shale is tough, brittle, thinly laminated and fissile, dark brown-grey to black and commonly sulphur-stained. Both coal and oil shale have been mined here, and the average distillation yield of the latter was 43 gallons of crude oil per ton and 26·7 lb ammonium sulphate (Willett and Wellman, 1940). More recent tests have indicated a maximum possible yield of 60–75 gal/ton (Elphick, 1959; Robinson and Dinneen, 1967).

The terrestrial beds pass upwards into a marine sequence of Whaingaroan–Duntroonian age (Oligocene). At variance with the characteristic Oligocene carbonate development as found in most other areas of New Zealand, these Landon beds in Southland consist mainly of thick clayey siltstones and mudstones. Greenish-grey clay shales and fine silty-sericitic mudstones with some thin, calcareous-argillaceous sandstone intercalations are several thousand feet thick east of the lower Waiau River. Near Blackmount – Redcliff Creek, where the Tertiary basin beween the Takitimu Volcanics and the Fiordland Complex is a mere 9 miles wide, the Oligocene marine mudstones are exposed in a near-vertical section some 2,000–3,000 ft thick, containing 2–8-in.-thick bands of concretionary, grey dense limestone which is slightly oil-smelling when freshly broken. Thin (1 in.) intercalations of laminated silt to fine sandstone are found occasionally.

Between Lake Te Anau and the Eglinton valley in the extreme north of the basin, the Oligocene is equally thick but consists mainly of hard thick-bedded, grey sandstone (Grindley, 1958). The basal 400 ft is poorly bedded dark, micaceous fine sandstone to siltstone, while the top portion is formed of blue-grey, calcareous mudstone.

Truly calcareous sequences occur only locally in the Oligocene, as for instance at Freestone Hill just east of Manapouri Township, where about 200–300 ft is exposed of mainly thick bedded, calcareous sandstone and grit. The rock (which forms high cavernous cliffs) is hard and well cemented, olive green and rich in quartz and biotite. Dense algal limestone of 100–150 ft thickness occurs at the Te Anau Glow Worm Caves (west shore of lake, north of Te Anau Township). This Tunnel Burn Limestone (McKellar, 1956) exposes wavy layering with thin laminated, arenaceous intercalations. It is highly calcareous and creamy in colour; the age is Duntroonian–Waitakian, thus Late Oligocene to Early Miocene. It is overlain by Lower Miocene, massive quartzose arkosic sandstone with a few thin, soft mudstone intercalations (Garden Point Formation of McKellar, 1956). Near Birchwood to the east of the Waiau valley (5 miles west of Ohai), the Oligocene is characterised by thin creamy limestone which alternates with mudstone, and calcareous sandstone 1–2 ft thick with shale intercalations. Also in the extreme south-east of the Waiau Basin, some thin-bedded shelly limestone occurs intercalated in micaceous silt-mudstone near the base of the marine Oligocene (Wood, in press).

Eastwards the Oligocene transgression reached as far as Gore, where the Chatton Marine Formation (Wood, 1956), consisting of shelly coarse sandstone, wedges out within the Gore Lignite Measures. The Pomahaka Estuarine Bed, located still further east, is probably the result of some shallow and temporary, maximum transgression which, however, did not submerge the whole land (Fleming, 1962).

The Lower to Middle Miocene formations, i.e., mainly the Southland Series (for which Southland is the type area) are undoubtedly the most remarkable formations here. Together with the Pareora Series which have not everwhere been recognised (Wood, in press), they are characterised by an extensive limestone development mostly in the form of biostromal banks. The most common rock type is skeletal and fragmental limestone of a polyzoan nature which generally is highly porous. It may be 100 or more feet thick in certain places, but is impersistent laterally where it grades into grey, micaceous siltstone and mudstone.

Limestone of the Lower Miocene Pareora Series is particularly well developed north of Invercargill where it is exposed in a chain of low hills nearly 20 miles long, from Fern Hill at the bank of Oreti River in the north to Forest Hill in the south. This Forest Hill Limestone, which is underlain by Oligocene greenish grey, silty micaceous and marly mudstone, is quarried in several places and consists of yellow, biogenic calcarenite of fair, but irregular bedding. It is said to be 200–400 ft thick on Winton Hill (Willett, 1950), while from Centre Bush Allan (1937) has described a detailed section whose total thickness is 90 ft:

60 ft of coarse grained, rudely stratified bryozoan limestone (calcarenite) with brachiopods throughout.
20 ft of fine-grained, massive limestone including two shell beds.
10 ft of coarse grained, impure, rubbly limestone with large brachiopods and pelecypods.
Fine-grained marl.

No limestone of Southland age is known from the Invercargill basin; the Forest Hill Limestone is overlain by poorly exposed sandy mudstone, while rocks in the Mataura valley to the east which supposedly are of Southland age consist of mainly terrestrial gravels, clay and lignite seams (Wood, 1966b).

In the Waiau Basin, the best section is exposed near Clifden where a thick limestone complex is made up of 100–120 ft of fairly well bedded calcarenites with Pareora Foraminifera and brachiopods, overlain by rather massive and grey, hard polyzoan limestone of Southland (Altonian) age; the two formations are commonly separated by a pebble band or limestone breccia of variable thickness, ranging from a few to 18 ft.

Directly above the limestones in the Clifden section is a 20-ft-thick bed of loose, whitish yellow quartz sand overlain by silt and impure, fine sandstone. Micaceous silt and silty mudstone with shell beds form the rest of the Southland Series. West of the Waiau Syncline, however, another limestone sequence occurs locally at the very top of this series (at Goldie Hill; Wood, in press).

The Upper Miocene Tongaporutuan to Kapitean sediments are thick fine grained, muddy to micaceous sandstones of grey-green to bluish colour. They probably are some 2,000–3,000 ft thick in the centre of the basin, but towards its margins, particularly on the western side, they overlap on successively older formations until at Port Craig, on the west shore of Te Waewae Bay, a Kapitean basal conglomerate comes to rest directly on basement (Wood, 1966b, in press). Thus there is a pronounced Upper Miocene transgression following widespread tectonic deformation and erosion, in the course of which marginal areas were uplifted and the present-day basins more closely defined. At this time the northern part (Te Anau) was probably cut off from the sea completely. A threshold or swell seems to have developed midway between the south coast and Te Anau, a sea arm having extended only into the southern portion of the Waiau Basin proper. North of it, thick deposits of silt, sand, and conglomerate of possibly Upper Miocene and certainly Plio-Pleistocene age are non-marine, lacustrine to fluviatile. To the south, the sea gradually retreated even further, and marine Pliocene is only found near the shore of Te Waewae Bay. In the Invercargill Basin to the east, the Upper Miocene to Pliocene history is little known due to the extensive Quaternary alluvial blanket which covers the plains; no marine rocks of these ages are known.

For any of the basins and particularly their deepest part, the total amount of subsidence is not well known, nor is the total sedimentary thickness. Geophysical work has indicated 11,000–12,000 ft for the Waiau Basin, while sediments in the Invercargill Basin would be not less than 6,000 and probably nearer to 10,000 ft thick (Hatherton, 1966). Recent deep drill-holes in the latter area reached basement at about 3,300 and 7,000 ft respectively (Kear, 1966b).

Potential Oil Formations

From the foregoing it follows that the only possible source for any oil or gas is in the basal coal measures and/or the Oligocene shales and mudstones.

Although the organic content in these rocks generally is low, and suitable carbonaceous silt-mudstones are seemingly not abundant in surface outcrops of the coal measures, these formations must nevertheless be considered as a possible source. Although their paleogeographic distributon and facies development are unknown across the large tracts of the basin where beds are concealed at depth, the existence of oil shales at Orepuki (although containing only little free hydrocarbon; cf. Robinson and Dinneen, 1967) is one indication that locally favourable conditions for the formation of bituminous rocks did exist. This Orepuki "field" represents a semi-closed basin about 2½ by 4 miles across, which during coal measure sedimentation may have been partly isolated from the main Waiau Basin to the northwest; the detailed mapping by Wood (1966b, in press) has shown the Orepuki beds to wedge out in that direction, and marine Oligocene directly overlies basement at Grindstone Creek. Similar conditions may have existed elsewhere underneath the basin, resulting in the formation of other bituminous rocks and the possible generation of free oil and gas.

Similarly, it cannot be ruled out that Upper Cretaceous Ohai Coal Measures could exist in subsurface in central parts of the basin, and in their turn contribute as a possible source. This is admittedly more remote particularly in view of the pronounced erosion which they suffered in pre-Eocene time, and their probably much more restricted original occurrence.

Oligocene marine shales are widespread and very thick, and on the whole more uniform. Although no results are known of any detailed investigation, their general aspect, dark colour and fine grain, together with the occurrence of definitely oil-smelling calcareous concretions, would suggest a favourable habitat for bituminous rocks in this series, and their being a possible source for petroleum. In fact, these beds are here considered of primary importance in this respect.

No younger beds appear to have a facies favourable for hydrocarbon generation. While the various limestones were all formed in very shallow and highly oxygenated water, the rest of the sequence is made up of clastics of fine silt-sand which are of grey-green to bluish and light grey-brown colours, generally rich in quartz and mica but evidently poor in any form of organic matter.

No direct oil indications are known, but one gas seepage has been discovered in Hindley Burn, a northern tributary stream of Lill Burn on the west flank of the great Waiau Syncline (Wood, 1966b). Gas is emanating, evidently through fractures, from foraminiferous grey silty claystone of the Upper Southland Series (Middle Miocene*). It contains 95·7% methane, including (from chromatograph anlaysis) very small amounts of ethane, propane, iso-butane, and normal butane (Wood, in press).

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*According to recent foram determination by Dr N. de B. Hornibrook, the rock in question is of Altonian (i.e., Lower Southland) age.

Potential storage rocks are found both in the coal measures and the Miocene limestone sequences. Massive quartz sandstones of fine to coarse grain and generally somewhat arkosic and micaceous composition occur in various coal measure sections, particularly east of the lower Waiau River and the high ridges west of the basin. A number of porosity measurements on such rocks which outcrop along the eastern margin have given values of 26%–37% porosity and several hundred millidarcies permeability, in one case as much as 6,120·0 md. Silt and shale breaks within the sandstones, and particularly the thick Oligocene mudstones should provide a suitable seal for such reservoirs.

The Lower and Middle Miocene limestone sequences perhaps form the most adequate, potential reservoir bodies. Their occurrence as large biostromes enhances their storage quality which thus is not bound entirely to structural conditions, but includes a particular potential for stratigraphic traps. Lateral facies change into impervious siltstone and mudstone furnishes a good possibility for traps up-dip on the basin flanks, while the thick cover of unconformable, Upper Miocene muddy siltstones provides an ample seal towards younger formations. Southland calcarenites near Clifden have given porosities from 23·8% to 34·4% and permeabilities between 87·0 and 226·0 md. In addition to these limestones, the 20 ft of loose quartzose sand as found in the Clifden section just above the limestone, if persistent, represent another potential reservoir bed.

CONCLUSIONS

In the light of this analysis of potential oil formations in the seven basins of New Zealand, some characteristic features common to all or at least some of them immediately become apparent (Table 2).

Possible Source and Reservoir Rocks Are in About the Same Stratigraphic Position

As the particular facies distribution pattern within each basin has not been investigated in detail, this could roughly be interpreted in terms of similarity of conditions for both source and reservoir rock deposition. In fact, both are comprised in a typical sand-shale assemblage, and their close relationship is evident in most areas. In one respect, this should enhance general petroleum prospects considerably, as free petroleum available, to be expelled during very early stages of compaction, would readily find associated reservoirs to allow accumulation and preservation.

On the other hand, similar conditions during sedimentation will result in the formation of deposits not very much different from each other. Rich source beds as well as good storage rocks could, under the circumstances, hardly be expected together, since an environment favourable for source facies is generally unfavourable for the accumulation of reservoir sediments and vice versa (Weeks, 1958). This certainly holds true for many New Zealand basins where, as a matter of fact, seemingly good source rock sequences and also direct evidence for the presence of petroleum or gas often exist in abundance, whereas good quality reservoirs are harder to find

TABLE 2—Stratigraphic Positions of Potential Oil Formations in New Zealand

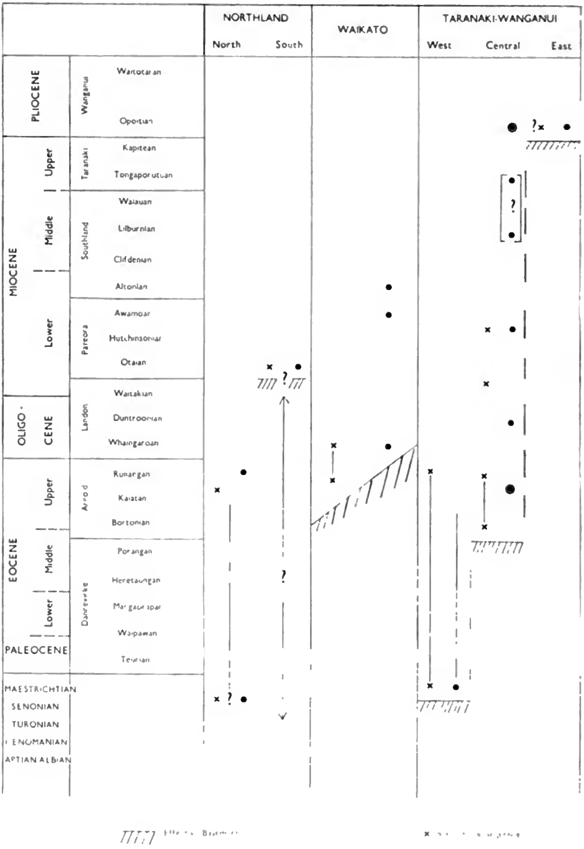
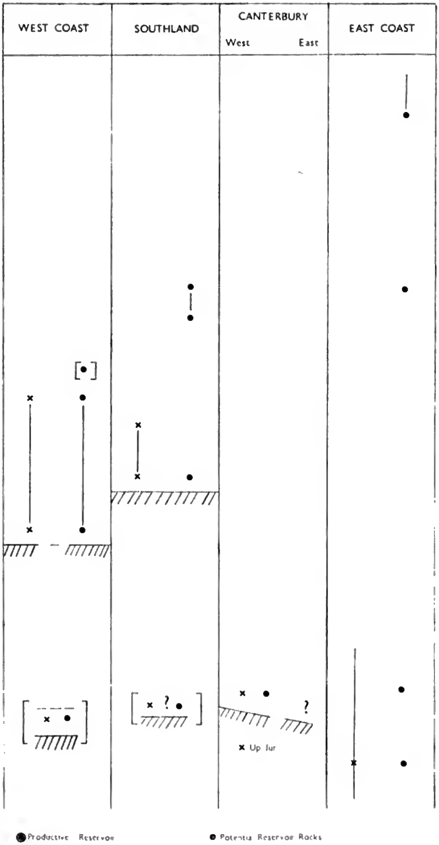


TABLE 2—*continued*



and evidently occur more rarely and restrictedly. This is the case in the East Coast Basin, for instance, and the opposite apparently is true in the Plio-Pleistocene Wanganui Basin.

Possible Oil Source Sequences Nearly Always Are Located at the Very Base of the Local Stratigraphic Column

Except from the Northland Basin where the geologic-tectonic relationships are still not well understood, and the East Coast Basin where a complex and highly differentiated miogeosyncline existed during Upper Cretaceous and Tertiary times, all the other basins are essentially characterised as unstable shelf areas or marginal deeps. They are typical epicontinental basins of various types, probably including open marginal basins of the continental coast. The decreasing rate of tectonic movement during the Cretaceous had allowed the formation of broad shelves across earlier stabilised areas, and the deposition of sand and fine mud across this subdued topography, often including coal measures at their base. Quite generally, conditions thus passed from continental sedimentation to a paralic, and then to a marine environment.

More specifically, it is this similarity of conditions during the beginning of the transgressive cycle in the Waikato, Taranaki, West Coast, Southland, and Canterbury Basins which created a strikingly similar depositional pattern, and which only became more differentiated during later stages of the individual tectonic evolution of each basin.

In all these five basins, the principal, if not only, rock sequence found to be a possible source for petroleum or gas is located at the base of the whole sedimentary succession (Table 2). This is consistent with the findings by Bitterli (1963) that "environmental conditions favourable for the formation of bituminous sequences . . . are often created at the turning points in the paleogeographic history . . . which may result in an incipient transgression or regression of the sea, possibly followed by a prolific plankton production and by stagnation". In fact, it is not uncommon for argillaceous sediments lying just above major unconformities to be good source rocks. Rich growth of organic material often took place on land during periods represented by such unconformities. This certainly was the case in the New Zealand basins where widespread coal measures occur at the base of the sedimentary sequence. Following subsidence and transgression, a certain stagnation may occur at a time when substantial amounts of organic material are available which then will be preserved, at least in part, and possibly be transformed into hydrocarbons (Fuloria, 1967). Also, such a favourable environment is by no means limited to stagnant waters but may have existed wherever prolific planktonic life flourished due to abundant nutrients present, as excessive development of plankton may create its own bottom-reducing conditions (Brongersma-Sanders, 1951).

If initial subsidence was slow and deposition rapid, widespread deltaic deposits may form where rivers deliver huge quantities of organic material, which is rapidly buried and therefore much of it preserved. As Rainwater (1963) has pointed out, traps are always available in the many porous discontinuous sand bodies deposited in and around deltas where oil and gas may accumulate as soon as they are formed. Much of the Kapuni Formation in the Taranaki Basin, as well as similar deposits elsewhere, may be particularly prospective because of these circumstances. The particular importance of deltas which arises from their transitional environments, from marine via estuarine to fluviatile, and their intermediate position between continental or cratonic and lacustrine or marine basins has been stressed by Bitterli (1963). His study also has shown that, although bituminous rocks are almost exclusively produced in aquatic environments, both transitional and limnic environments are at least as favourable as marine ones; in fact, non-marine bituminous sequences contain, on an average, much more organic material, i.e., higher concentrations, than marine ones. It is perhaps significant that the greater part of recent, new discoveries of oil occurrences throughout the world is associated with fresh or brackish formation water; although this may partly be due to flushing, most of them are thought to have originated in sediments deposited in waters of less than marine salinity (Hedberg, 1964). The transitional, often terrestrial-paralic environments of much of the possible oil source sequences in the five basins here mentioned probably are typical, and are thought to be indicative for the particular tectonic setting in which these sequences have been formed. Their lithologic assemblage is, according to Hedberg's recent (1967) classification, of the shale-sandstone-coal type which includes the probable source strata of many major petroleum occurrences throughout the world.

The nature of the unconformity below the transgressive cycle thus appears as a controlling factor with respect to source rock sequences. Their stratigraphic position at the base of the whole sedimentary succession in all these New Zealand basins is probably a consequence of the uniform and relatively quiet tectonic process which pre-dated transgression, and which culminated in the formation of low mature lands. The paleogeographic turning point, evidently important for the generation of bituminous rock sequences here, had arrived when sedimentation definitely started on a new cycle, first perhaps with the terrestrial-paralic to estuarine deposits, followed later by a full-scale marine transgression. This happened in Senonian or Maestrichtian time in some basins, but only in the Eocene or Oligocene in others.

Most Potential Reservoir Formations Are Also Near the Base of the Sedimentary Sequence

The sand-shale facies of the unstable shelf which characterises these deposits lacks several of the more prominent reservoir type rocks such as quartzose blanket sands, calcareous and dolomitic reefs, etc. Depending on the sediment source, subgreywackes or arkosic sandstones are predominant, and their silt-clay or micaceous component generally is considerable; dirty, dense, and tight silt-sandstones are the rule.

However, the particular sedimentary processes involved before or at the time of transgression, i.e., in the lowermost part of the stratigraphic sequence, have caused a local cleaning-up of sands around deltas and where channel and near-shore currents were active; in addition, prolonged weathering and leaching of the source area has led to a concentration of quartzose material in the non-marine basal deposits in some basins, particularly in the Brunner Coal Measures of the west coast. The near-pure quartz sands in Canterbury have been mentioned as an exceptional type, possibly formed as a terrestrial deposit but located on the fringe of the transgressive sea; it was probably derived, partly at least, from a decaying rhyolite source.

It becomes evident therefore that the presence of potential reservoir formations preferably near the base of the sedimentary sequence is to a great measure due to the particular environment of these basins and their tectonic evolution.

Occasionally Potential Reservoir Formations Occur Higher Up in the Stratigraphic Section

Here, also, their presence is closely related to the local tectonic history, and they include sandstones as well as limestones.

Neritic shelf limestones which are partly porous and potential storage rocks are known from northern Taranaki, Westland, and Southland. They all mark a stage in the geological history when influx of terrestrial detritus was minimal and the land adjacent to the basins was certainly worn down more than at any other time. The porosity of these limestones is mainly caused by their fossiliferous, skeletal, or fragmental lithology. Those in Taranaki and west coast of the South Island of Oligocene age, were deposited when transgression had reached its greatest extension, whereas the Miocene limestones in Southland were probably formed when the sea was already in a regressive phase. Here the apparent random distribution of these epineritic biostromal limestones within an otherwise silt-mudstone facies indicates an open shelf environment, but probably situated well below wave base. Increasing tectonic unrest and renewed erosion on land caused muddy silt to fine sand to accumulate higher up in the sequence, while repeated occurrence of shell beds towards the top of the Southland Series demonstrates continued regression. This initiated the phase of structural deformation and strong erosion which in the Upper Miocene extended at least to areas within the margins of the present Waiau Basin, as shown by the unconformable Taranaki Series.

Shelf sandstones of Miocene and Pliocene age form additional potential reservoirs in the East Coast, Taranaki, and Waikato Basins. The thick Middle to Upper Miocene sandstones on the East Coast are related to a major change in sedimentation with increased influx of coarser material particularly from the west, while at the same time local basins of rapid subsidence were filled with flysch-type deposits devoid of potential storage rocks. Further south along the East Coast Basin, possible reservoir formations are those overlying the pre-Miocene unconformity, and as such are related to the advancing diastrophism of the Kaikoura Orogeny. In like manner in the Taranki Basin, the Mokau Sandstone, probably the most prospective apart from the Kapuni Formation, was deposited when the Patea–Tongaporutu High ceased to be active, while at the same time sediment from the west had begun to reach the area. It is particularly developed therefore in that direction, but additional sand was brought into the basin from the north-east across the still active Ohura Fault. Both in the Taranaki and Wanganui Basins, good clean sands were deposited during the Pliocene because of its particularly high-energy environment, and in Moturoa producible oil has actually accumulated in such sands. Finally, prospective Waitemata Group sandstones in the Waikato Basin are restricted to a position near the unconformity with the underlying Te Kuiti Group sediments, and represent the beginning of a new sedimentary cycle in a near-shore, shallow marine environment.

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ENGINEERING GEOLOGY OF THE PARINGA–HAAST SECTION OF STATE HIGHWAY SIX, SOUTH WESTLAND

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ABSTRACT

This report considers some of the engineering-geological factors affecting the choice of route to complete the last 30 miles of State Highway Six between Paringa and Haast in South Westland. It briefly discusses the geology of the area and some of the geological problems subsequently encountered during road and culvert construction.

INTRODUCTION

General

In 1962 the Director of the New Zealand Geological Survey was asked by the Commissioner of Works for a geological appraisal of the two alternative routes then under consideration to complete State Highway Six. Completion of the last 30 miles of this road would link the townships of Paringa and Haast in south Westland and give road access for the first time from north Westland to Otago via the Haast Pass. As a result an appraisal of the geological aspects of the project was made and a recommendation communicated to the Ministry of Works.

Following this recommendation and the subsequent start of road construction, geologists of the New Zealand Geological Survey maintained a close association with the project. This report briefly records the geology of the area and details some of the engineering-geological problems encountered during and after road and culvert construction.

Location and Topography

The area described lies between the Paringa and Haast Rivers in south Westland, New Zealand (Fig. 1), and includes two main types of country. Between the township of Paringa and the Whakapohai River the road crosses low lying, poorly drained, young-valley fill deposits and Last Glaciation outwash gravels. From the Haast River north to Bullock Creek the road runs partly through similar terrain and partly along the crests of young, well drained beach ridges. Between Bullock Creek and the Whakapohai River, however, the topography is steep and rugged, rising to about 1,300 ft above sea level, with many small, deeply incised streams draining densely bushed coastal faces (Fig. 2).

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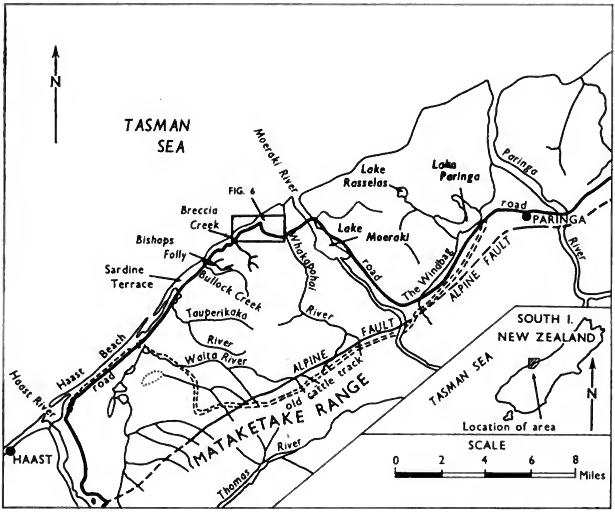


FIG. 1—Locality map showing the road route, the Alpine Fault, and the Cattle Track from Haast to Paringa.

Length and Standard of Road

About 30 miles of road are included in the area covered by this report. The carriage-way for most of this distance is 28 ft wide with curves in the steep coastal section generally being designed for faster than 25 mph, although a few curves are down to 20 mph. The maximum grade is 1 in 12.

Field Work

The geology of the area was briefly described by Wellman (1955) and mapped at a scale of 1 : 63,360, but for the purpose of the engineering-geological survey this was inadequate.

The initial geological survey to assess the various routes then under consideration by the Ministry of Works was carried out by Messrs H. S. Gair and D. R. Gregg assisted by E. T. Annear and the writer, between 12–19 April 1962. They were accompanied for part of this time by the Ministry of Works engineer-in-charge, Mr T. C. H. Mouat, of Paringa.

Geological traverses were made of the two main routes, all the major streams, and many of the minor streams, as well as the coastline. As a result the stratigraphical succession was established and the distribution of the principal rock units mapped at a scale of 1 : 7,920. Some modifications have since been made to this mapping but on the whole they have been relatively minor except in two important respects, namely the discovery of an additional major fault in Grave Creek, and of extensive areas of raised beach deposits.

Following completion of this survey and the start of road construction the writer was responsible for the engineering-geological aspects of road building and culvert and bridge construction.

GEOLOGY

It is not intended to deal in detail with the geology of the region but only to consider the various rock units in so far as it is necessary to outline the rock types and establish the sequence.

Schistose Greywacke and Argillite

The oldest rocks of the area are the unfossiliferous schistose greywacke and argillite of the lower Paleozoic or Precambrian Greenland Group. Generally the rocks strike roughly east–west and dip to the north, usually steeper than 45°. The greywacke and argillite are particularly hard but well jointed, a factor of some significance in road building.

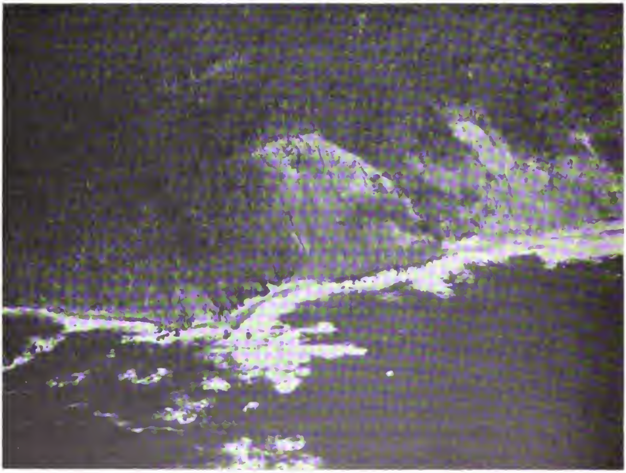


FIG. 2—Steep coastal country typical of that traversed by the road between Bullock Creek and the Whakapohai River.

The present road crosses only two narrow infaulted bands of greywacke; south of Murphy Creek (Fig. 6) where there is a band about 20 chains wide, and north-west of the Whakapohai Bridge where a second band about 30 chains wide crosses the road. All contacts are faulted.

Non Marine Sandstone and Conglomerate

The oldest rocks of a much later period of sedimentation are beds of Upper Cretaceous and Lower Tertiary non-marine quartz and greywacke-sandstone, and quartz, greywacke and granite conglomerate with thin lenses of coal and carbonaceous shale. This formation is about 800 ft thick between Knights Point (Fig. 6) and Murphy Creek where it is in fault contact with greywacke and argillite. Further south in the region of Bishops Folly and Bullock Creek (Fig. 1) it may be appreciably thicker, but the sequence here is complicated by folding.

The beds strike north-east, roughly parallel with the coast, and in most places are overturned to the south-east at angles in excess of 50° (Fig. 3).

The lower (eastern) contact with the Greenland Group is faulted by Arnott Fault.

Glauconitic Sandstone

A Lower Tertiary, massive, coarse, green-grey or brown, marine glauconitic sandstone conformably overlies the coal measures. It is of unknown thickness but 430 ft is present in Grave Creek, and mapping near Bullock Creek indicates a thickness of about 1,500 ft. These beds strike parallel to the coastline and the road, and dip between 45° E (overturned) and 70° W.

Basalt, Agglomerate, Tuff

The glauconitic sandstone is conformably overlain by a variable thickness of Lower Tertiary tuff which occurs with agglomerate and flow basalt, the products of submarine volcanism. The basalt is massive and hard, and includes some pillow lavas and many calcite veins. The tuff and agglomerate on the other hand are much softer and weather readily into a dark brown "greasy" soil.

Blue-Grey Siltstone and Limestone

The volcanics are overlain by about 70 ft of hard, impure, blue-grey to white, highly contorted, muddy limestone (Fig. 4). The limestone is of Middle Tertiary age and is poorly exposed in the upper parts of Breccia and Grave creeks. Along the road line south of Murphy Creek it is infaulted, with calcareous blue-grey siltstone, into Greenland Group rocks.

Raised Beach Deposits

At least four raised beaches are preserved along or near the road alignment. They occur at about 40 ft, 70 ft, 150–170 ft, and 420–440 ft above mean sea level. Quartz gravel at an altitude of about 1,200 ft on the ridge between the headwaters of Grave and Mistake creeks (Fig. 6), although possibly residual gravel derived from Cretaceous and Tertiary conglomerates, may represent a former, much higher, stand of sea level.

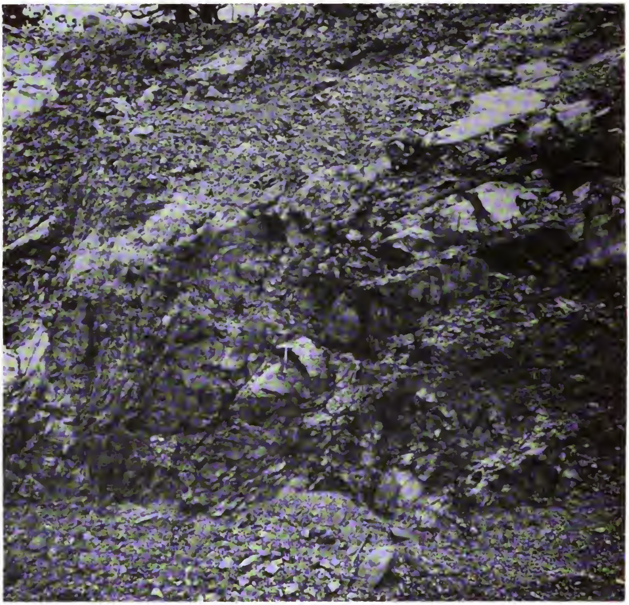


FIG. 3—Broken and fractured non-marine sandstone and conglomerate near Murphy Creek. These beds are overturned. Some blasting of this material was necessary here, and along the coast south of Grave Creek.

The 420–440 ft raised beach is the most important from the road building point of view. It is widest at Knights Point (Fig. 5) where it is over 100 yd wide, but elsewhere a width of only 20–40 yd has been preserved along the steep coastal faces. The gravel lenses within it are slightly folded and the surface has been moderately dissected by the few small streams that cross it. As a result this beach now appears as an undulating surface. Its gravels are not strongly cemented, although several partially cemented bands 3–4 in. thick do project from the face of the outcrop. Most of the material of this beach has been locally derived, particularly the many agglomerate boulders which come from nearby volcanics.

An extensive raised beach, Sardine Terrace, lies near the north end of Haast Beach between Ship and Bullock creeks. Its surface, again undulating, is mostly between 150–170 ft above sea level, and beach gravel at 170 ft,

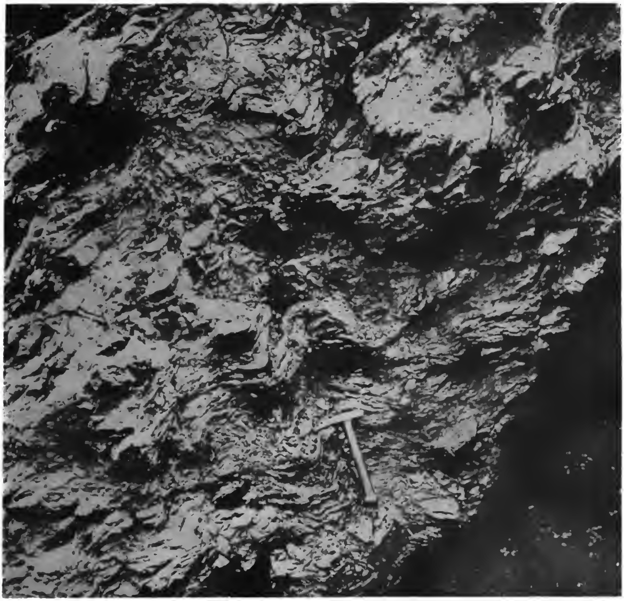


FIG. 4—Severely contorted, hard Tertiary limestone near Venture Creek.

3 miles to the north between Bullock and Breccia creeks, is probably a remnant of the same beach. Sixteen feet of well rounded beach gravel and sand composd of quartz, fresh greywacke, and schist, and capping morainic silts, sands, and boulders, is exposed in fresh road cuts south of Bullock Creek (Fig. 14A). These beds unconformably overlie probable Upper Cretaceous coal measures. Wellman and Willett (1942) discussed Sardine Terrace, mentioning that black sands interbedded with its deposits were worked for their gold content.

The other benches at 40 ft and 70 ft are not important to this road.

Recent River and Swamp Alluvium, Dune Sands

Most of the Paringa–Haast section of the road has been built on these materials with certain precautions (e.g., removal of the larger felled trees from swamp areas before filling) being needed in some areas, particularly on the heavily forested, poorly drained flats north of Haast River, and between Lakes Paringa and Moeraki.

FAULTS

The area is broken by three sub-parallel major faults and many less important smaller faults, all of which are marked by crush zones consisting of badly shattered and pugged rock. The most important is the Arnott Fault which influenced the location of the road crossing in Breccia Creek and adversely and seriously affected road construction and subsequent road maintenance in the vicinity of Grave Creek. The location of this fault in the Breccia–Grave–Murphy creeks is shown on Fig. 6, and Figs. 7 and 13 depict some of its features. Although Arnott Fault strikes roughly north-east it is quite sinuous suggesting a rather shallow dip. However, slickensided surfaces and the attitude of material within its crush zone show that in fact it dips very steeply to the south-east.

In Grave Creek the severely pugged and crushed rock of this fault zone is at least 1,000 ft wide, with a narrower but still extensive zone of minor crushing each side of this. Fig. 7 shows the extent to which the rocks of this zone have been shattered by fault movement. The crush zone consists of blocks of greywacke and argillite up to about 4 ft through, in a matrix

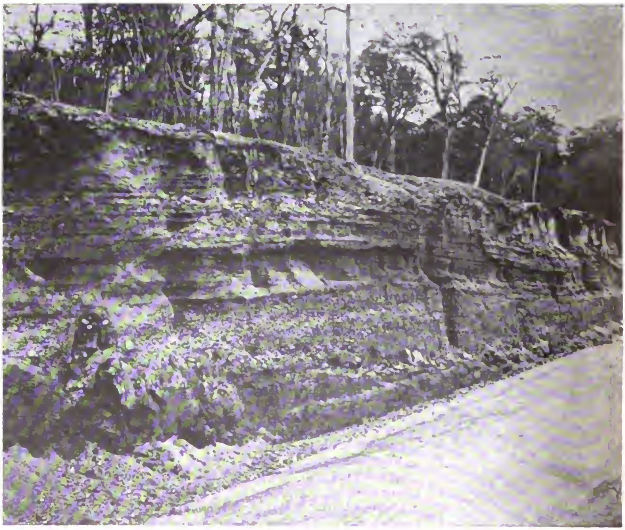
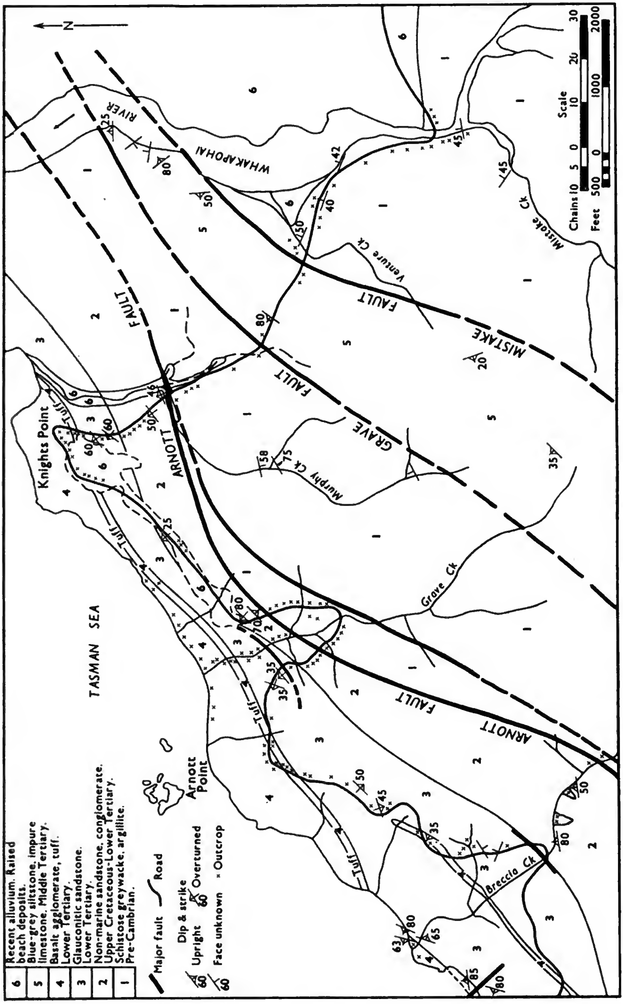


FIG. 5—Pleistocene beach gravels 420 ft above sea level at Knights Point. The extent of these gravels was underestimated in the early stages of the survey and they later significantly affected the overburden-bedrock ratio. Note that they are slightly deformed.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6 Recent alluvium. Raised beach deposits.
5 Blue-grey siltstone, impure limestone. Middle Tertiary.
4 Basalt agglomerate, tuff. Lower Tertiary.
3 Glauconitic sandstone. Lower Tertiary.
2 Non-marine sandstone, conglomerate. Upper Cretaceous-Lower Tertiary.
1 Schistose greywacke, argillite. Pre-Cambrian.
Major fault
Road
Dip & strike
Upright
Overturned
Face unknown
Outcrop
TASMAN SEA
Arnott Point
Knights Point
Tuff
WHAKAPOHAI RIVER
ARNOTT FAULT
GRAVE FAULT
MISTAKE FAULT
Venture Ck
Murphy Ck
Grave Ck
Mistake Ck
Breccia Ck
Scale
Chains 10 5 0 10 20 30
Feet 500 0 1000 2000

FIG. 6—Geological map of the Knights Point – Breccia Creek area.

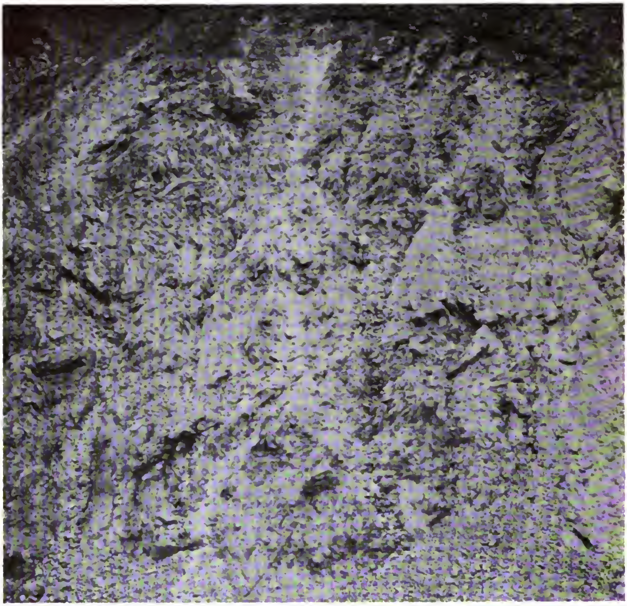

FIG. 7—Shattered and pugged greywacke and argillite at Arnott Fault in Grave Creek. This zone is about 700 ft wide.

of very soft, wet, fault pug which can be easily moulded in the hand, and which, when wet, acts as an excellent lubricant. The Arnott Fault brings greywacke and argillite into contact with coal-measure sandstone and siltstone.

As is usual where rock types of differing hardness are affected by faulting the harder rock is the more shattered and broken. In Grave Creek and in Breccia Creek this is true, the coal measures being much less fractured, even close to the fault zone, than the very hard greywacke and argillite.

The Arnott Fault has been traced northwards from Bullock Creek through Breccia Creek to Grave Creek, where its strike suggests it should intersect the coastline at about Knights Point. However, continuous exposures along the road and at beach level at Knights Point fail to reveal it, and Arnott Fault evidently swings sharply east to Murphy Creek where severely shattered greywacke is in fault contact with carbonaceous quartz sandstone at the road crossing.

Grave Fault

Although Grave Fault is a major feature bringing greywacke and argillite into contact with Upper Tertiary calcareous siltstone and impure limestone it is not exposed along the roadline. However, it has been accurately located in Bullock, Breccia, and Grave creeks, and its position is known to within 2 chains where it crosses the road midway between Venture and Murphy creeks. Wherever it is exposed severe crushing is evident.

Mistake Fault

A 15-ft zone of pugged greywacke in Venture Creek is the only known exposure of Mistake Fault. This fault brings calcareous siltstone and limestone into contact with greywacke along a line roughly parallel with and about 20 chains to the north of Mistake Creek. Both this fault and Grave Fault are only crossed by the road once, whereas Arnott Fault is crossed at least three times.

INFLUENCE OF GEOLOGY ON CHOICE OF ROAD ROUTE

Although the New Zealand Geological Survey was approached in 1962 to advise on the most suitable of the two main routes along the coast then being considered, geology had in fact influenced a decision on the location of the road much earlier.

Before the completion and opening of the Paringa–Haast section of the road in 1965 the only reasonable access to Haast from North Westland, other than by air, was the Cattle Track. This route along which cattle from Haast and further south were driven north for sale was along Haast Beach to Waiata River, and thence inland towards a series of low saddles along the front of the Mataketake Range 5–8 miles inland. The track crossed the Moeraki River about 8 miles from the coast and followed The Windbag Creek northwards to Lake Paringa (Fig. 1). It might have been expected, since this track was well graded and of a high standard, that the new road southwards would have followed its general route. However, for 8 or 9 miles between the Moeraki River and Coppermine Creek, the Cattle Track follows the Alpine Fault, probably being within its crush zone for most of this distance. The width of the crush zone associated with the Alpine Fault in this region is not known, but on the basis of knowledge elsewhere it is likely to be at least 200 ft, and possibly up to 1 mile wide. Further north in Westland, particularly between Fox Glacier and the Waikukupa River, major slips associated with the Alpine Fault have caused serious road maintenance problems. As a consequence one of the main reasons a route south via the apparently more difficult coastal country was chosen was to avoid similar difficulties to be expected in the immediate vicinity of the Alpine Fault. However, this decision was made some time before the Geological Survey was approached, and it is mentioned here only for its interest.

In the Whakapohai River to Bullock Creek section of the Paringa–Haast Road two main alternative routes were being considered. These were known as the "coastal" and "inland" routes, although it should be noted that the "inland" route was not more than 1½ miles from the sea in any place. The basic difference between them was that the coastal route was all less than 650 ft above sea level, whereas the proposed inland route climbed much higher, to 1,311 ft.

Geologically the main disadvantage of the inland route was that much of it lay within severely crushed beds of calcareous siltstone and impure limestone within which severe slipping was expected. Although this route crossed all of the major faults the crossings were generally at about right angles and would therefore probably not be too troublesome.

Geologically the main advantage of the coastal route was that much of it would be constructed in massive, marine, glauconitic sandstone, and in coal measure conglomerate, sandstone, and siltstone. The main disadvantage was the uncertainty of the position of Arnott Fault between Grave and Murphy creeks where it was apparent that the proposed road and the fault were roughly parallel and close together. It was expected that shattered rocks associated with Arnott Fault would lead to some slipping.

As a result of the geological survey it was concluded (Gair and Gregg, 1962): "On the basis of geology there is little to choose between the two routes. There is a slight preference for the coastal route because the formations along the coast are more massive and less broken by faulting."

ESTIMATION OF OVERBURDEN–BEDROCK RATIOS

An attempt was made (Young, 1963) to estimate the thickness of overburden present along the road line, by this time firmly chosen as the coastal route, and to estimate the percentage of bedrock that could probably be shifted by a Caterpillar D8 or equivalent bulldozer without recourse to ripping or blasting. Rugged, portable, single channel, refraction seismographs are ideally suited for this type of investigation and such an instrument would undoubtedly have been of considerable value for this survey. However, in 1962 the techniques were relatively new overseas and untried in New Zealand, and there was insufficient time for one to be obtained, calibrated, and applied. As a consequence only standard geological field techniques were used.

From the appearance of the slopes along the road line, particularly their steepness, and from an estimate of how readily the various geological formations weathered, a minimum average thickness of 10 ft of overburden was suggested. That is, at each major cut along the 8 miles of road it was assumed that an average of 10 ft of soft material would overlie solid rock. Then for each of the rock types known to be present beneath this overburden an estimate was made of the probable percentage that could be shifted without recourse to ripping or blasting. Three broad categories of rock type were involved.

Greywacke and Argillite

Although very hard, these rocks are commonly badly broken and jointed (Fig. 8) and it was thought that they, for the most part, could be bulldozed. However, a few hard more massive bands were expected to be present and it was suggested that 20% of the greywacke should be considered as solid rock.

Sandstone and Conglomerate

This group consisted mostly of hard, massive, poorly jointed, glauconitic, marine sandstone, and similar non-marine sandstone and siltstone with much smaller areas of quartz conglomerate. Because of the massive, poorly jointed nature of the sandstone it was not thought that this could be bulldozed, but because of the probable presence of soft, more jointed, weathered, or faulted zones an allowance of 20% was made for material that might be more easily removed.

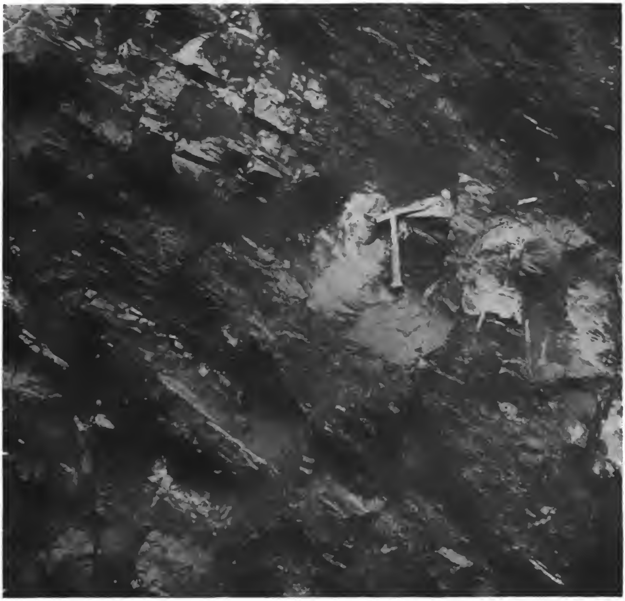

FIG. 8—Typical jointing in beds of greywacke and argillite near the Whakapohai Bridge. The argillite is clearly more broken than the greywacke on which the hammer rests.

Basalt, Tuff, Agglomerate

The road line traversed about 40 chains of this material but it was not known at the time to what extent it would lie within basalt as distinct from the tuff and agglomerate. The basalt was considered to be too hard to bulldoze, the tuff and agglomerate to be soft and readily shifted.

On the whole these predictions proved reasonably accurate in that the greywacke, tuff, and agglomerate could be bulldozed, and the basalt at Knights Point, and much of the glauconitic sandstone between Grave and Breccia creeks and at Murphy Creek was either ripped or blasted. However, in total there was much less blasting over the full length of the road than anticipated. This was largely because of the presence of the 420–440 ft raised beach along the coast (Fig. 5), and because of the very extensive zone of shattered rock on both sides of Grave Creek.

Between the time these estimates were made and the calling of tenders a bulldozed access track was constructed along the road line from the Whakapohai River almost to Grave Creek. The outcrops which resulted, in an area previously devoid of outcrops, proved most valuable and revealed the previously unsuspected presence of the 420–440 ft raised beach.

By its nature an estimate of this type can only be very approximate because of the large number of unknown factors involved. The most serious of these factors was the lack of knowledge about the rock type at each major road cut. This information can be gained by trenching or drilling, but the cost involved, and in this case the lack of time available between the choice of route and the completion of the engineering survey, and the calling of tenders, made this impracticable. In addition to the benefits to be gained from improved access for engineers, surveyors, and prospective tenderers, therefore, the track to Grave Creek provided much geological information which, had it been available earlier, would have been of considerable value.

GEOLOGICAL CONSIDERATIONS AFFECTING THE CHOICE BETWEEN BRIDGE OR CULVERT CONSTRUCTION

For the 17 small river and stream crossings between the Whakapohai River and Bullock Creek there was no doubt that culverts or large pipes would be the most suitable form of bridging because the creeks carried little water, had steep gradients, and fairly small catchments.

For the two largest crossings, the Whakapohai River and Bullock Creek, bridges were clearly the most desirable because of the large volume of water these rivers carry in flood times, the relatively unrestricted nature of their beds, and because bridge construction could proceed at both places without interfering with the progress of road construction.

The situation with respect to the Murphy, Grave, and Breccia creek crossings, however, was not quite so straightforward, and the construction of bridges or culverts was considered.

The main geological reasons for deciding to build large culverts instead of bridges were the nature of the topography and bedrock at the sites and the small amount of debris which could block the culvert carried by the streams during times of flood.

Because of the deeply incised, tortuous nature of all the streams between the Whakapohai River and Bullock Creek large trees seldom move far from the place at which they fall, very soon becoming jammed in the valley floor. For this reason one often serious disadvantage restricting the use of culverts did not apply.

ENGINEERING GEOLOGY OF MAJOR CULVERT SITES

Murphy Creek

With a catchment area of 240 acres and a total run-off of about 735 cusecs at 3 in. rainfall per hour, this is the smallest of the three major streams across which a culvert was constructed. The culvert is situated in a flat-floored valley about 40 yd wide 5 chains upstream from a low swampy area. It is 147 ft long, 20 ft wide, and 14 ft 2 in. high.

To test the gravel of Murphy Creek and provide some geological information six test holes were drilled with a small portable, petrol driven diamond drill using 5 ft E rods and a 4 ft 6 in. core barrel. Three holes were drilled under each proposed abutment. Although core recovery in the gravels was very poor it was possible to determine depth to bedrock.

Four of the drillholes, to depths of 20, 20, 11, and 24 ft respectively were all still in Recent alluvium, but two drillholes on the north abutment penetrated soft, broken quartz sandstone and quartz conglomerate at 12 ft. This material may have been *in situ* but a test pit sunk to 14 ft near one of these holes was still in river gravels. The gravel was predominantly well graded, river-worn greywacke and although several soft layers were encountered during drilling the material was expected by Ministry of Works personnel to have a high bearing capacity.

Following the completion of the foundation investigations and the design of the culvert it was learned that Arnott Fault almost certainly passed through the culvert site. The depth beneath the river gravel at which bedrock occurs, however, is generally in excess of 20 ft, and as the alluvium almost certainly has a lower bearing capacity than the shattered rock associated with the fault, the effect of Arnott Fault at the culvert site was expected to be negligible.

Subsequent Behaviour of Murphy Creek Culvert

Before completion of Murphy Creek culvert a measuring programme was designed by Ministry of Works personnel to determine the amount of settlement of the abutments and slab and the deflection of the arch following the placing of the fill. Four checks, including the initial "as constructed" measurements were made over a period of 12 weeks.

Fig. 9 is a settlement graph for the middle portion of the culvert. Curves 4 and 6 are at construction joints at each end of the middle section of the Paringa and Haast abutments, and Curve 5 is at a construction joint in the middle of this section which is, in effect, acting as a beam. Most of the settlement, about 3 in., occurred in the centre of the culvert where

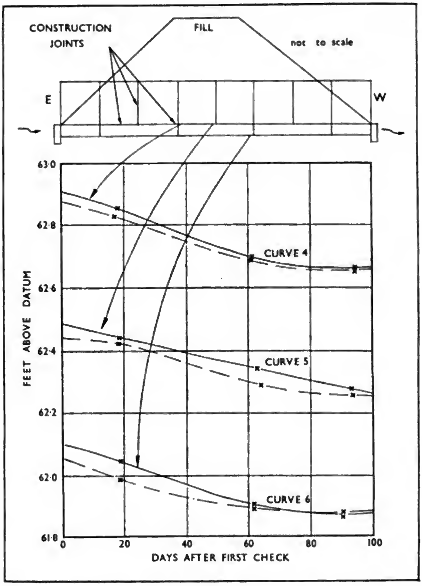

FIG. 9—Settlement graph for Murphy Creek Culvert. The solid lines are for the Paringa abutment. The broken lines for the Haast abutment.

the amount of cover and therefore the load was the greatest. The first two checks were made when the culvert was only partially covered, and the third and fourth after all of the fill had been placed and compacted. In sympathy with this the graph shows that most settlement occurred immediately after the placing of the fill. However, the Haast abutment at section 6 settled rapidly immediately following its completion, even before the fill was completed, while the Paringa abutment at section 5 settled at an apparently uniform rate throughout. All the curves except the latter indicate that settlement had apparently ceased within 100 days of construction and loading.

The effects of this settlement can be seen clearly within the culvert. The two most obvious results are spreading of ⅜ in. at the base of the construction joints (Fig. 10), and the projection by about 2 in. of the concrete invert slab above the abutment in the centre of the culvert (Fig. 11). The invert slab was initially poured level with the shoulder of the abutment but settlement of the abutment has left the slab perched above it. Numerous fine cracks and some spalling have also occurred.

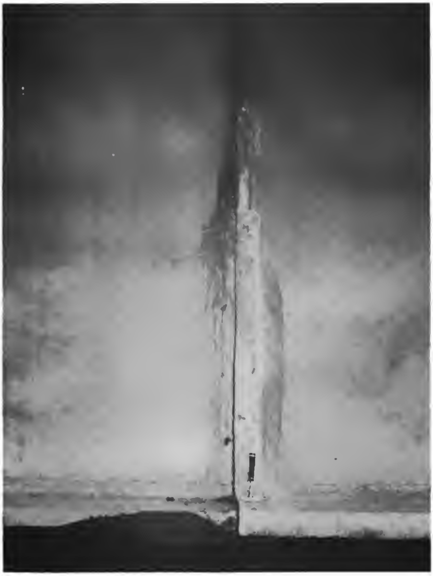

FIG. 10—Deformed construction joint in Murphy Creek Culvert. Note that the gap is about ⅜ in. wide at the bottom and decreases in width upwards.

Reasons for Settlement

Because, as shown by Fig. 9, stability was attained fairly rapidly the primary reason for settlement was probably a reduction in volume (compaction) of the foundation materials following the expulsion of water in response to the loads applied.

Grave Creek

With an estimated run-off of 1,173 cusecs at 3 in. rainfall/hr from a catchment of nearly 400 acres, Grave Creek is a much larger waterway than Murphy Creek. The culvert, consisting of 113 2-ft-wide concrete arches bolted together, is 226 ft long, 25 ft wide, and 21 ft high. It is covered with about 40 ft of fill.

During the planning stages it was known that a branch of Arnott Fault crossed Grave Creek 40–60 ft downstream from the culvert site, and it was suspected that some young, partially overgrown slips on the east bank upstream from the site might also have a fault origin. No good outcrops occurred in the vicinity of the culvert site although some large blocks were doubtfully considered to be in place. Later it was found that Arnott Fault was a very much larger feature than initially thought, and that in Grave Creek its crush zone was of the order of 800 ft wide. It passes diagonally through the culvert site and its crush zone extends from 700 ft downstream to 500 ft upstream (Fig. 6).

Because the zone was so wide little was to be gained by resiting the structure. Shifting the culvert site downstream about 700 ft would have ensured that the road and culvert were constructed in relatively sound coal measure sandstone. However, as the culvert would then have been about 75 ft lower, either the gradient of the road down to it would need to have been steepened appreciably, or the fill over the culvert increased accordingly. On the other hand, to resite the culvert 500 ft upstream beyond the crush zone in reasonably sound greywacke and argillite would have entailed constructing 20 chains more road within the fault zone. Because of the large amount of slipping that was already being experienced at the time this was an unattractive alternative to building the culvert in the position initially chosen, even though the bearing capacity of the material was suspect.

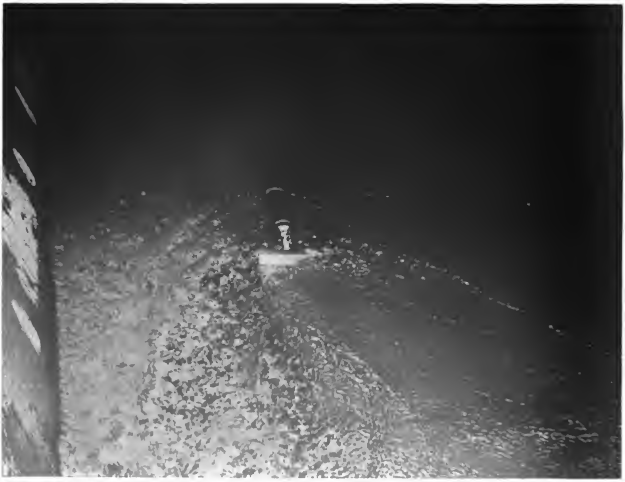

FIG. 11—Photograph in the Murphy Creek Culvert showing the invert slab projecting above the abutment by about 2 in. Before settlement of the abutments these were level.

The material on which the culvert was constructed is badly shattered greywacke and argillite. It is light green-grey in colour because of the plentiful presence of fault pug, and contains angular greywacke blocks up to 3 ft in diameter (Fig. 7). The pug is not present as discrete layers or zones except for occasional partings of less than ½ in., but rather the pug is intimately mixed among the larger greywacke blocks. The material is in place and for practical purposes can be considered as a reasonably solid mass when dry and undisturbed. When wet, however, the pug becomes very slippery and tends to act as a lubricant within which the larger greywacke blocks are transported as a slurry if not confined. Because of this characteristic it was obvious that the bearing properties of the material would be appreciably less than for solid greywacke. As a result the design-bearing intensity of the culvert footings was reduced from 10 tons/sq ft to about 7 tons/sq ft by increasing the width of the footings from 4 ft to 6 ft. In addition, to protect the shattered material in the floor of the culvert from erosion by Grave Creek and to keep the rock beneath the footings as dry as possible, it was decided to include a concrete invert slab in its design.

Following completion of the culvert in August 1965 several measurements were made, as at Murphy Creek, to determine its subsequent behaviour. Unlike those of Murphy Creek culvert the abutments have settled very little; the maximum settlement of about ¾ in. has occurred near the centre of the culvert, tapering off to nothing at both ends. The central construction joint has opened slightly and a few hair cracks in the concrete lining are also apparent.

On the whole, however, it appears as though the foundation material is quite capable of supporting the structure. Nevertheless, because some settlement has occurred (although very minor) it would appear that the decision to increase the width of the footings and to pave the floor of the culvert was justified.

Breccia Creek

The design of the Breccia Creek culvert is identical to that at Grave Creek except that it is only 170 ft in length. The culvert, not completed at the time of writing, lies partly over the boundary between hard, massive, glauconitic, marine sandstone and well bedded, carbonaceous, non-marine sandstone and conglomerate. Elsewhere in the area the boundary appears to be gradational, but at the culvert it is a faulted contact, with a few inches of fault pug exposed in the creek bed. In spite of this, and in spite of some other minor faults and the somewhat fractured and folded nature of the coal measures (Fig. 12), this is geologically the best site of the three discussed.

GEOLOGY OF MAJOR SLUMPED AREAS

Serious slumping occurred in two regions following road construction and in both cases the cause is apparently closely related to the geology of the area.

During the road planning stages a report on the stability of the slopes along the proposed route was prepared by the New Zealand Geological Survey (Young, 1963). In the report the route was divided into six sections

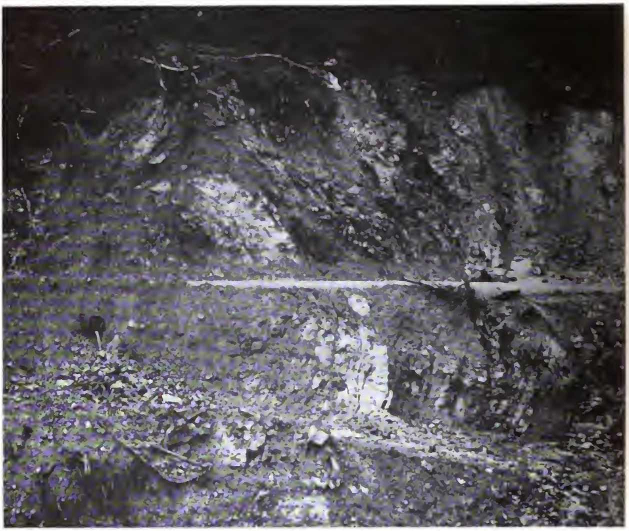

FIG. 12—Coal measures at Breccia Creek Culvert site showing their folded and broken nature. Several faults occur here with up to about 8 in. of fault pug along the fault lines.

in order of potential instability. The main geological factors considered in this assessment were the location of fault zones, the attitude of the strata and their relationship to the road line, the soundness of the rock, and the gradient of the slope.

Because of the suspected presence of Arnott Fault and the steepness of the slope there, the northern side of Grave Creek was considered potentially the least stable of the six sections. In practice this has proved to be so because, since this section of the road was opened up, prolonged and continuing trouble has been experienced. When dry the slopes are reasonably stable but rain invariably changes this material into a wet, slippery, unstable mass which flows downhill carrying the road with it. A slip now extends well above road level (Fig. 13) and to date, 12 months after construction, it shows little evidence of stabilising. No serious attempts to drain the water from the slope have been made and it is unlikely that they would meet with success until the worst of the slipping has occurred and a reasonably stable angle of rest is attained. The geological reason for the slip is undoubtedly the crushed and broken nature of the rock associated with Grave Fault.

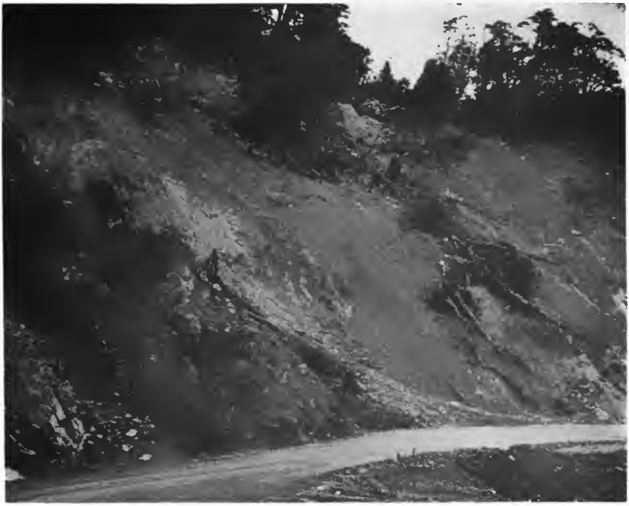

FIG. 13—Severe slumping within the Arnott Fault zone at Grave Creek. Twelve months after construction there were no indications that this area was stabilising.

Another major slip occurred soon after road construction between 20 and 30 chains south of Breccia Creek. Two possible reasons exist for the instability of this area.

The most likely cause of slipping lies in the fact that the glauconitic sandstone and coal measure beds within which the slip has occurred strike roughly parallel to the road and dip towards it at a moderate angle. Undercutting of these beds during road construction has possibly led to the instability. A second factor, probably associated with the former, and perhaps of major importance, is that the zone of shattered rock (Fig. 12) occurring at the non-marine sandstone - marine glauconitic sandstone boundary in this area (but not elsewhere) crosses the slumped area.

It is not possible without a very full investigation to state to what extent this material will continue to slump, but there are some indications that the re-aligned portion of the road may now be on or close to bedrock, which although still moderately shattered, is possibly in place.

Similar potential "greasy back" conditions exist 10–12 chains south of Breccia Creek where glauconitic sandstone dips seawards at about 45°. However, the topography here is such that the potential slip surface does not intersect the coal measure - glauconitic sandstone boundary, and as a result only relatively minor slipping, when compared with a major slip, is likely to occur.

Several relatively large slips, generally below road level, have occurred along the coast where the basalt is either thin or missing. Elsewhere the relatively unstable glauconitic sandstone is apparently protected from sea erosion by the basalt.

ROCK TYPES AND THEIR INFLUENCE ON BATTER ANGLES

Fig. 14 shows the batter angle one year after construction for four types of lithology. The rock types which stand best vertically are Pleistocene marine gravel and sand and glacial gravel and sand (Fig. 14A). It is common in Westland and elsewhere to have vertical batter angles in this relatively soft, semi-consolidated material. When it does fall the material tends to drop off as a thin slab, thereby preserving a vertical face.

The greywacke and argillite are also satisfactory (Fig. 14B) when they are not too severely shattered, although the large number of joints generally occurring in argillite (Fig. 8) leads to the almost continuous shedding of small blocks in freeze-and-thaw conditions, or during heavy rain. Fig. 13 illustrates the effect of severe faulting in this material.

On the whole the marine and non-marine sandstone stands reasonably well (Fig. 14C) and provided the larger trees are removed from the edges of the higher cuts no trouble is experienced except where the beds dip towards an excavation.

The least stable material not affected by faulting encountered along the road was the agglomerate and tuff at Knights Point (Fig. 14D). It weathers readily into small lumps which accumulate at the foot of the face.

GENERAL COMMENTS

Portable Seismograph

In 1962, when most of the engineering geology for the Paringa–Haast road was undertaken, portable seismographs were still being developed overseas and none were available in New Zealand. These instruments measure the transmission speed of longitudinal waves generated usually, but not necessarily, by an explosive charge. From the velocity of these waves reasonably accurate estimates of the rippability and bearing capacity of the material through which they pass, to a depth of about 100 ft, becomes possible. The instrument, which can be operated by one person but usually has a crew of four or five, is rugged and portable and as such is suited for use in steep terrain.

Use of a portable seismograph would have been invaluable for determining the bearing capacity of the foundation material at the Murphy and Grave Creek culvert sites, and would have helped materially in determining the nature of the excavations along the route. However, bearing in mind the size of the crew and the nature of the terrain, such a major seismic survey would undoubtedly have been costly and time consuming and, of course, much of the information that it would have been yielded was obtained later when the access track was built. Nevertheless, in spite of this, it is clear that portable seismographs are a valuable tool for this and many other types of engineering-geological investigations involving subsurface conditions.

Access Track

Before the calling of tenders, but after much of the geological work and surveying were completed, an access track was bulldozed approximately along the proposed road line. This was primarily intended to assist prospective tenderers to gain an appreciation of the project, but its value as a time saver for surveyors and others cannot be overemphasised. In addition it provided valuable outcrop data along the road line where few previously existed, and it presented the country in a much more favourable light because of the psychological effect of easier access. Not all projects of this type warrant the formation of an access track, but the saving in man hours consequent on its presence in this case suggests that a similar approach may be worth while in other steep, heavily bushed areas.

Bedding Tests for Culvert Sites

The major problem found by the writer in his studies of the various culvert sites was the lack of quantitative data on which to base conclusions concerning the bearing capacity of the various rock types. Apart from the use of a portable seismograph the most suitable method would probably have been some adaptation of the California Bearing Ratio Method. This would need to have been modified to a form suitable for use in the field on coarser samples than those normally determined. So far as is known no such method exists but at Murphy and Grave creeks in particular, quantitative data that could have been compared with other known conditions would have been valuable.

Drilling

Valuable information was gained from the relatively limited amount of drilling undertaken on the project but it was found advantageous for a geologist to be readily available in order to guide the drillers with respect to drilling depths. For instance, at Grave Creek culvert site it was known that greywacke was the bedrock. The information required was gravel thickness so that as soon as the drill had clearly penetrated the alluvium there was no need to drill further. Unless a geologist is readily available the only other approach to this problem is to either instruct the drillers to drill all holes to a uniform, perhaps excessive depth, or trust to his knowledge of the problem.

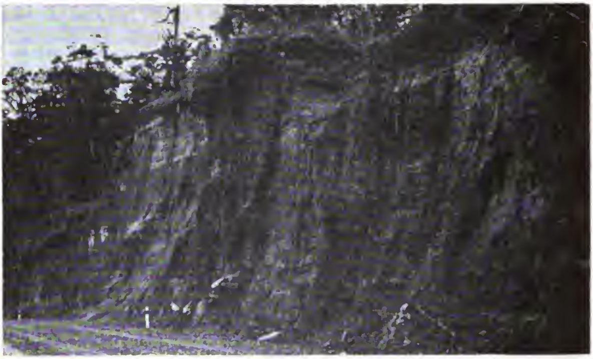

FIG. 14A

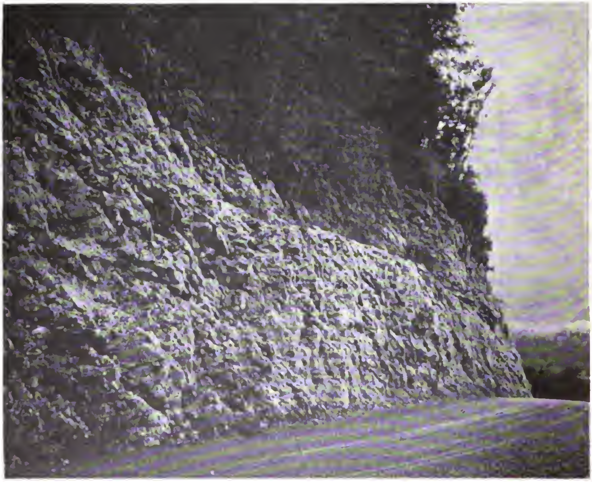

FIG. 14B

FIG.. 14—Four photographs illustrating the influence of rock type on batter angle. (A) Pleistocene beach gravel. (B) Greywacke and argillite. (C) Non-marine sandstone and siltstone. (D) Tuff and agglomerate. Note that the beach gravel, although soft, stands vertically; that, where not faulted, greywacke and non-marine sandstone and siltstone stand well, and that the tuff and agglomerate are the least satisfactory. For the effect of faulting on (B) see Fig. 13.

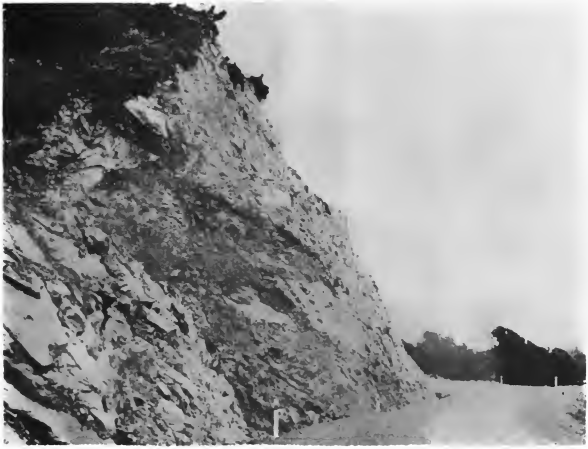

FIG. 14C

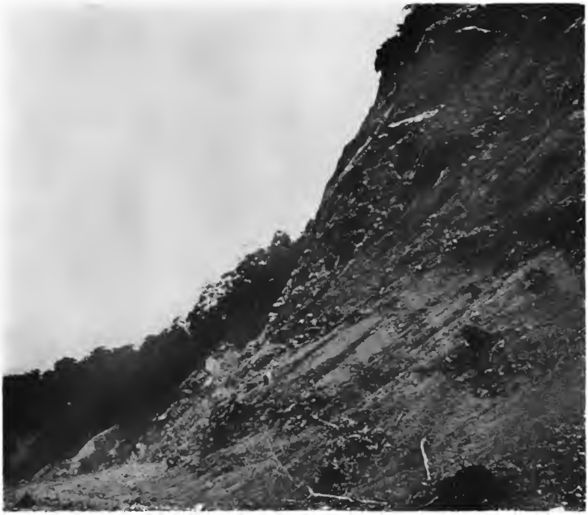

FIG. 14D

ACKNOWLEDGMENTS

The writer is particularly indebted to Mr T. C. H. Mouat, Senior Engineer-in-Charge of the project at Paringa, for his assistance, advice, and co-operation throughout. Other Ministry of Works personnel, particularly Mr H. A. Grigg, Resident Engineer, Greymouth, and Mr J. Ford are also thanked for their assistance.

The initial report prepared by Messrs H. S. Gair and D. R. Gregg of the New Zealand Geological Survey, Christchurch, was freely consulted during the writing of this report.

Valuable assistance and advice were received from Mr L. E. Oborn, Mr D. R. Gregg, and Mr W. A. Sara during the preparation of the manuscript.

The measurements on which Fig. 9 is based were made by Mr N. C. McGeorge, Ministry of Works, and their use here is gratefully acknowledged. The photographs were taken by Mr D. L. Homer, New Zealand Geological Survey, Lower Hutt. The maps were drafted under the supervision of Mr C. T. T. Webb, Cartographic Section, Information Service, Department of Scientific and Industrial Research.

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OBSERVATIONS ON THE DEBORAH VOLCANIC FORMATION NEAR KAKANUI, NEW ZEALAND

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ABSTRACT

The Deborah Volcanic Formation near Kakanui, South Island, New Zealand, consists of lapilli tuffs from two eruptions of alkaline olivine basalt or atlantite (Tuffs I and II) and a final eruption of melanephelinite (Mineral Breccia Member). The field relations and the topography of the lavas are described.

INTRODUCTION

The Deborah Volcanic Formation near Kakanui, South Island, New Zealand (Fig. 1), contains lapilli tuffs from three periods of volcanic eruption. These tuff deposits are here named, in order of deposition: Tuff I, Tuff II, and the Mineral Breccia Member. The Mineral Breccia Member contains peridotitic, eclogitic, and other volcanic xenoliths which were first described by Mantell (1850) and later discussed by Thomson (1905, 1907), Turner (1942), Benson (1944), Roedder (1965), and Mason (1966). The results of a recent petrologic examination of these xenoliths, conducted at the University of Otago, appear elsewhere (Dickey, 1968).

REGIONAL SETTING

Tertiary volcanism in the Kakanui area began during the late Eocene with submarine eruptions of basaltic tuff and emplacement of hypabyssal intrusives of the Waiareka Volcanic Formation. This formation is succeeded by the Totara Limestone, an upper Eocene, tuffaceous biomicrite. The Deborah Volcanic Formation lies on the Totara Limestone and is overlain by a middle Oligocene biosparrudite, the McDonald Limestone. Additional details on the regional geology will be found in Gage (1957) and Coombs and Dickey (1965).

THE DEBORAH VOLCANIC FORMATION

The distribution of outcrops of the Deborah Volcanic Formation near Kakanui is shown in Fig. 1†. Exposures are continuous along the coast but rare inland. The tuffs and adjacent sediments have been gently folded along north-west–south-east axes and tilted slightly toward the south-east. The

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†The grid marks on the borders of the map are based on the national thousand-yard grid shown on Sheet S136 of the 1 : 63,360 topographical map series (NZMS 1).

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thickness of the tuff deposits varies considerably. The type section of the formation, along the south bank of the Kakanui River estuary is 38 ft thick (Gage, 1957). In this section Tuffs I and II are not clearly defined. Together they form 36 ft of grey and brown lapilli tuff which lie, with some slumping at the contact, upon Totara Limestone. Above Tuffs I and II, 2 ft of calcareous tuff with xenocrystal fragments represent the Mineral Breccia Member. The top of the formation was here eroded before deposition of the McDonald Limestone. Elsewhere the tuffs are more voluminous. Along the sea coast north of the river mouth are continuous exposures of 150 ft of Mineral Breccia Member, 150–200 ft of Tuff II and 55 ft of Tuff I.

The tuffs of the Deborah Volcanic Formation contain glassy and crystalline lapilli, which are much altered to palagonite, zeolites (chiefly a member of the phillipsite group), and a montmorillonoid mineral. The pyroclastics, including bombs and rare blocks of lava, are cemented together by carbonates and zeolites. Often the Mineral Breccia Member is greenish grey, bearing a superficial resemblance to the blue ground of kimberlite pipes; Tuffs I and II, however, are typically salmon pink or reddish brown. This colour difference is apparently caused by a preponderance of crystalline lapilli in the Mineral Breccia Member and tachylite lapilli in Tuffs I and II. The three tuff units are separated by angular unconformities, one of which is shown in Fig. 2.

Bioclastic dikes of hard, tuffaceous biomicrite with glauconite and detrital quartz are exposed in the Mineral Breccia Member near Gee Point. Seldom more than 6 in. thick, these dikes can be traced through more than 20 ft of pyroclastic beds. Many of them represent multiple intrusions. In colour they vary from milky white to yellow green. Among the Foraminifera, Polyzoa, and echinoderm remains in the dikes are *Cheilogumbelina ototara* and *Globigerapsis index* (Dr N. de B. Hornibrook, pers. comm.) which restrict the age of the source material to the Kaiatan or Runangan Stages and, therefore, imply derivation from either the underlying Waiareka Volcanic Formation or, more likely, the Totara Limestone.

PETROGRAPHY OF THE LAVAS

Bombs and blocks of lava in the tuffs indicate that the Mineral Breccia Member formed from a melanephelinite magma, whereas alkaline olivine basalt or atlantite magmas produced Tuffs I and II.

The melanephelinite of the Mineral Breccia Member contains, in its groundmass, a fine-grained mat of titaniferous augite laths, skeletal apatite prisms, magnetite grains, and micropoikilitic nepheline. Plagioclase is absent. The major constituents of the rock are sub-idiomorphic pseudomorphs after olivine and phenocrysts of titaniferous augite. The augite is sometimes fresh, but the olivine is always replaced by carbonate and a green mineral, possibly celadonite. Much of the rock is altered to zeolites and carbonate.

Minute laths of titaniferous augite predominate in the groundmass of bombs from Tuffs I and II; plagioclase (An_{50}) and an opaque oxide are also present; nepheline may be an obscure constituent. The abundance of plagioclase is variable, but it is always there. Titaniferous augite and olivine form sub-idiomorphic phenocrysts. They are usually pseudomorphed by carbonate, greenish material, and iddingsite.

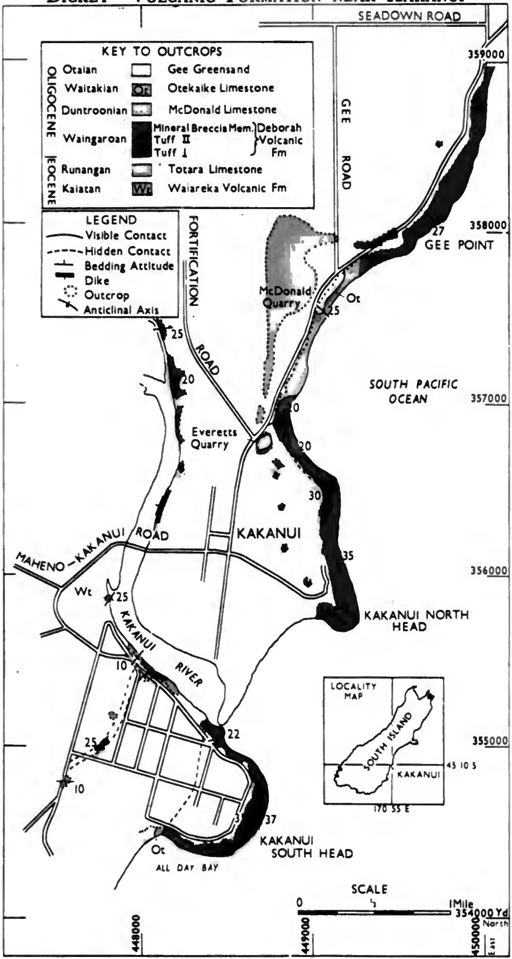

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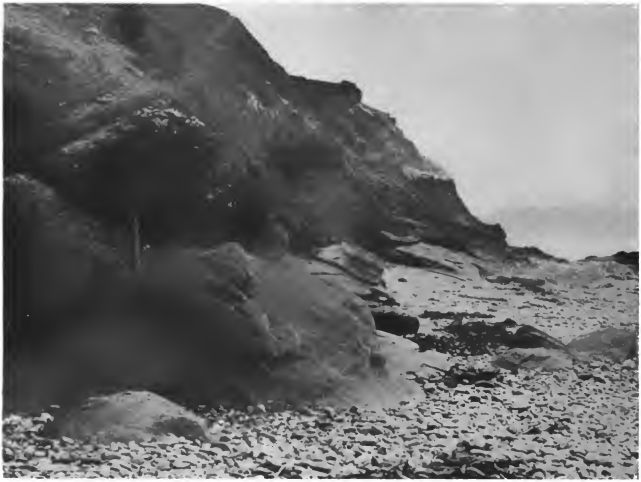
FIG. 1—Map showing rock outcrops at Kakanui.



R. H. Hardie, photo

FIG. 2—Westward-dipping beds of the Mineral Breccia Member lying unconformably on eastward dipping beds of Tuff II. South Head, Kakanui.

A less altered representative of the magma which produced either Tuff I or II may be the steeply dipping dike intruding lower tuffs of the Deborah Volcanic Formation on the eastern shore of the Kakanui River, about 100 yd upstream from the highway bridge (Fig. 1). The groundmass of this basalt is predominantly plagioclase (An_{50}) accompanied by opaque grains, probably homogeneous magnetite-ulvöspinel solutions (Mr J. B. Wright, pers. comm.), and minute prisms of a clinopyroxene. Neither analcite nor any feldspathoid has been identified in the rock. Sub-idiomorphic phenocrysts of olivine (Fo_{88}) and titaniferous augite are common. Pyrite of sub-idiomorphic and globular habit has been observed in minor concentrations, possibly with rare chalcopyrite (Mr J. B. Wright, pers. comm.). Rounded quartz xenocrysts, derived probably from the underlying schists, are surrounded by reaction rims of augite crystals. The slight alteration of the rocks has been to carbonate and zeolites.

CONCLUDING REMARKS

Thomson (1905) recognised a "mineral breccia" and a "barren breccia" at Kakanui, and he noted (1907) that the "mineral breccia" formed from limburgite magma, whereas the "barren breccia" formed from olivine basalt magma. The "barren breccia" is now regarded as two deposits, Tuffs I and II. The compositional difference which Thomson discovered is here confirmed and more completely described. This change in composition should be considered in any discussion of the origin of the xenoliths in the Mineral Breccia Member.

ACKNOWLEDGMENTS

I wish to thank Professor D. S. Coombs for his instruction, assistance, and encouragement; the U.S. Government for a Fulbright Scholarship which enabled me to do this work; the University of Otago for research facilities; Mr and Mrs T. E. Liddell, of Kakanui, for their hospitality; and my field assistant, Mrs Joan Dickey.

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HYDROTHERMAL ASSOCIATION OF PYROPHYLLITE, KAOLINITE, DIASPORE, DICKITE, AND QUARTZ IN THE COROMANDEL AREA, NEW ZEALAND

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ABSTRACT

Hydrothermal action has formed a clay deposit with a zone containing over 80% pyrophyllite and other zones containing kaolinite–dickite–quartz and kaolinite–diaspore from andesite in the Coromandel area New Zealand. The deposit was formed deep in the earth at pressures over 2,000 p.s.i. and temperatures above 335°C. The pyrophyllite in the deposits has the formula

$$[Al(OH)_2]^+_{0.1}\ Al_2\ [Si_{3.90}Al_{0.10}]\ O_{9.95}(OH)_{2.10},$$

and an X-ray diffraction pattern and differential thermogram similar to, but not identical with, those given in the literature. Dickite and lepidocrocite were identified in the deposits by X-ray diffraction techniques; diaspore by X-ray diffraction and optical techniques.

INTRODUCTION

Examples of the effects of hydrothermal solutions upon rocks are common throughout New Zealand in geothermal areas and wherever ore minerals have been deposited from sulphide solutions. Few studies using modern clay mineralogical techniques have been made of the mineralogical changes produced in rocks by these solutions.

The alteration at Wairakei has been studied in detail by Steiner (1953). Hydrothermal solutions have altered and are still altering tuffaceous and arenaceous rocks, but not interbedded argillaceous rocks, which are nearly impervious. He found four main zones, with kaolinite, alunite, and opal occurring in the sulphuric acid leaching zone near the surface; kaolin, montmorillonite, and pyrite in a zone of argillisation; the zeolites, ptilolite and analcite, in an intermediate zone; and adularia in the hottest zone.

The minerals produced by hydrothermal action depend on the original chemical and mineralogical composition of the altered rock, composition of the altering solutions, temperature, pressure, and time. Nearly 100 different minerals are recorded as having been formed by hydrothermal alteration, and it is probably safe to say that any mineral formed by weathering has also been formed by hydrothermal alteration. The converse is not true. The

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solutions which occur in weathering have a much smaller range in composition than hydrothermal solutions, and the ranges of temperatures and pressures are also much smaller. In consequence, minerals which are well outside the stability field of weathering can be produced by hydrothermal action. These minerals are therefore susceptible to attack by weathering after hydrothermal alteration. In many cases, the pink and bright red colours commonly associated with hydrothermal deposits are due to the subsequent oxidation by weathering of pyrite produced by hydrothermal action.

Halloysite and monoclinic kaolinite are very common products of both weathering and hydrothermal alteration, but nacrite, dickite, and probably triclinic kaolinite are formed only by hydrothermal alteration. As Swindale (1957) has pointed out, the last three minerals have highly ordered crystal structures and the conditions under which they will form must be much more exact than the conditions which will produce the relatively disordered kaolinite and greatly disordered halloysite. Kerr (1955) says that field relationships show that dickite is usually formed under deeper-seated conditions, and is usually, if not always, of hydrothermal origin.

Pyrophyllite, of particular importance in this study, his never been shown to have been formed by weathering, but Meixner (1937), Kimizuka (1938), and Zen (1961) have suggested that it can be formed during low-grade metamorphism. It is usually formed by hydrothermal alteration.

This report deals with the results of an investigation of some clays formed by hydrothermal alteration in the Coromandel Peninsula. The first authentic reports of the minerals pyrophyllite and dickite in New Zealand are given. Two other unusual minerals, diaspore and lepidocrocite, were also found.

LOCATION AND GENERAL DESCRIPTION OF THE DEPOSIT

Location

The deposit is about 1 mile north of Tairua, on the east coast of the Coromandel Peninsula. It forms the prominent, white, rounded hillock of Pukepaukena (N.Z.M.S. 1, Sheet N44/338451), to the east of the Tairua–Whitianga road as it winds from the township up and over the Tairua Hill.

General Geological Description

Pukepaukena was mapped, without comment, by Bell and Fraser (1912) as a siliceous sinter deposit occurring within or upon propylitised andesite of the Beeson's Island Series. The andesites, which occupy an area along the coast from Tairua to Hot Water Beach, are mainly hypersthene- or pyroxene- andesite lavas, but they are everywhere altered to some degree. The extent of the alteration is not described for these particular rocks, but, in the commonest type of alteration in the region, pyroxenes and hornblendes are partially altered to chlorite and carbonates. In the regions of mineral veins the alteration is more intense, with sericite, quartz, and carbonate occurring in place of the original andesitic minerals.

The andesitic rocks between Tairua and Hot Water Beach are bounded to the west by Tertiary rhyolites and dacites. Amongst these rocks many remnants of volcanic plateaus can be seen, at heights ranging from 1,500 to 2,500 ft above sea level. The andesites, on the other hand, are deeply dissected, and rise in this area to a maximum elevation of 904 ft. Although differential earth movements and the general downwarping of the area make it impossible to deduce much from these differences in altitude, it seems certain that several hundred feet of andesites have been eroded away to expose the mineral veins and hydrothermally altered rocks.

Description of Deposit

The mound of Pukepaukena projects some 50–100 ft above the surrounding countryside. It is shaped, in plan, roughly like the sounding-box of a fiddle (a botanist might call it panduriform), with its longer axis lying east–west. A sketch of the plan of the dome, taken from an aerial photograph, is shown in Fig. 1. The dome is about 7 chains long and 3½ chains across, and has a a surface area of about 1½ acres.

Running across the dome, from approximately south-west to north-east, is a band of siliceous sinter, which may mark the fissure from which the original solutions issued. The siliceous sinter separates the mound into western and eastern parts, of which the eastern is much the larger.

Seven separate zones are recognisable in an exposed bank on the western side of the siliceous sinter. They are named and shown in plan and section in Fig. 1. The names indicate the main mineralogical constitutents found in them. Although the exposure is only 7 ft high there is evidence that the zones continue for 50–100 ft down the hillside.

The part of Pukepaukena to the east of the siliceous sinter was examined only at surface outcrops. It consists of white and light brown, highly altered, cemented kaolin rock.

Brown, white, and purplish, friable, non-sticky clays are exposed, some with relict structure of the original rock, about 3 chains north of the main western exposure. This material is considered to constitute the outer zone of weathered, regionally altered andesite.

DESCRIPTION OF SAMPLES TAKEN AND RESULTS

Representative chip and clay samples were taken from all zones of the western part. Several grab samples were taken from the eastern part, the siliceous sinter, and the outer zone. Chemical analyses of representative samples from the western part of the deposit are given in Table 1. Chemical analyses for the $<2\,\mu$ clay from some of the zones are given in Table 2. Figs. 2 and 3 show X-ray diffraction patterns and differential thermograms respectively for samples of particular interest. A summary of the mineralogical compositions of the various zones and parts is given in Table 3.

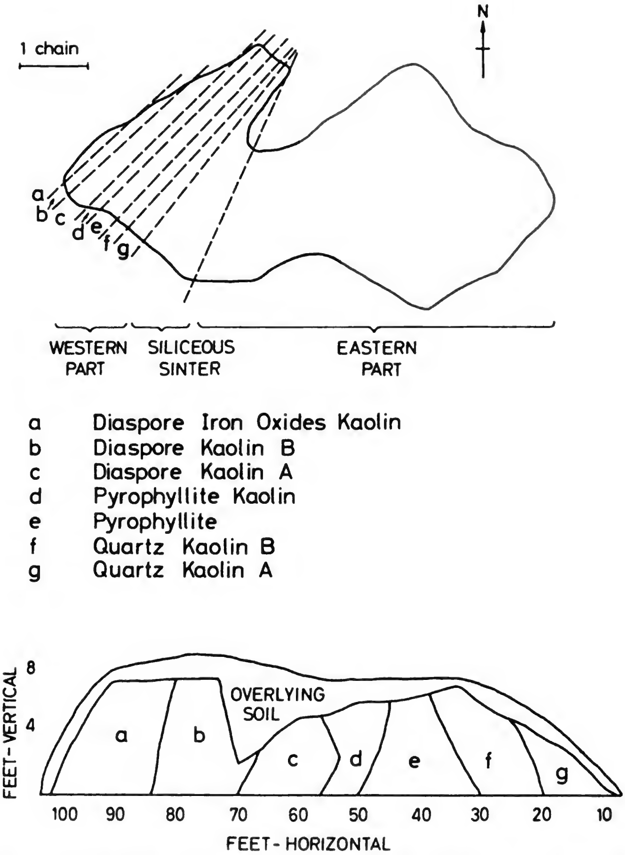


FIG. 1—Pukepaukena. Upper: plan showing parts and zones. Lower: section of western part.

TABLE 1—Chemical Analyses of Whole Samples from Western Part and Outer Zone

	Western Part							Outer Zone
	Quartz kaolin *A*	Quartz kaolin *B*	Pyrophyllite	Pyrophyllite kaolin	Diaspore kaolin *A*	Diaspore kaolin *B*	Diaspore-iron oxide-kaolin	
Sample No.	63/101	63/102	62/7	62/8	63/105	63/106	63/107	62/10
	%	%	%	%	%	%	%	%
SiO_2	56·0	48·5	60·5	45·2	43·7	43·0	40·3	49·1
TiO_2	0·4	0·4	0·2	0·2	0·2	0·2	0·3	0·2
Al_2O_3	30·7	37·0	30·9	37·9	40·1	38·6	37·5	34·2
Fe_2O_3	0·6	0·6	1·1	3·0	1·5	3·7	7·3	1·7
CaO	–	–	0·4	0·4	–	0·1	–	0·8
MgO	–	–	0·1	0·1	traces	traces	–	0·4
Na_2O	0·2	0·2	0·2	0·1	0·1	0·3	–	0·4
K_2O	<0·1	<0·1	traces	0·1	<0·1	<0·1	–	0·1
$H_2O(+)$	11·4	13·0	6·8	13·0	13·5	13·5	13·6	12·8
$H_2O(-)$	0·7	0·3	–	–	0·6	0·6	1·0	–

TABLE 2—Chemical Analyses of the $<2\ \mu$ Fractions

Zone	Pyrophyllite	Pyrophyllite kaolin	Diaspore kaolin *A*
Sample No.	62/7	62/8	62/9
	%	%	%
SiO_2	62·7	45·9	41·5
TiO_2	–	0·4	0·5
Al_2O_3	29·7	37·0	41·7
Fe_2O_3	1·0	2·8	0·8
CaO	–	0·2	0·1
MgO	–	0·1	traces
Na_2O	0·2	0·2	0·3
K_2O	–	0·1	0·2
$H_2O(+)$	5·8	12·6	14·6
$H_2O(-)$	0·6	0·7	0·3

The Western Part

Quartz-Kaolin Zone A—brown stained, cemented clay

The main mineral component of this zone is kaolinite, which makes up about 75% of the zone. There is about 20% quartz, 3–5% dickite (in addition to the kaolinite), and small amounts of mica and iron oxides or sulphides. A chemical analysis of sample 63/101 is shown in Table 1. The occurrence of dickite, which has not been previously recorded in New Zealand, is discussed more fully in a later section.

Quartz-Kaolin Zone B—white, cemented clay

Kaolinite is also the major constituent of this zone, comprising about 85% of the total. About 7% quartz, 5% pyrophyllite, a little dickite, and a trace of mica make up the remaining minerals. A chemical analysis of sample 63/102 is given in Table 2, and it can be seen that the Fe_2O_3 content of this zone, like that of the previous zone, is very low.

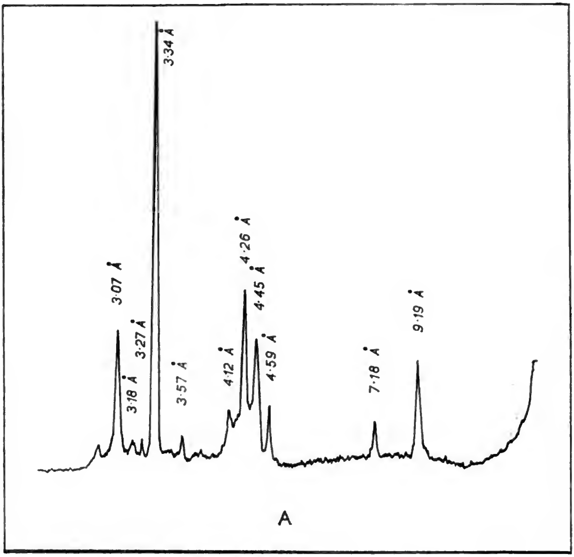


FIG. 2—X-ray diffraction patterns using relatively unoriented powder samples. A—Representative sample from pyrophyllite zone showing pyrophyllite, quartz, and kaolin.

Pyrophyllite Zone—vari-coloured clay

The zone contains approximately 80% pyrophyllite, 5% each of quartz and kaolinite, and small amounts of cristobalite, dickite, and pyrite. Both X-ray diffraction patterns (Fig. 2) and differential thermograms (Fig. 3) are characteristic of pyrophyllite. In the differential thermogram a pronounced exothermic peak occurs at 320°C as a result of the oxidation of pyrite. A chemical analysis of a representative sample is shown in Table 1. There is almost a complete absence of alkali and alkaline earth oxides. When the chemical components of the above minerals are calculated and compared with the chemical analysis, some 6% Al_2O_3 and 2% H_2O remain unaccounted for. These are approximately the proportions of 8% of gibbsite ($Al(OH)_3$), but neither gibbsite nor any other crystalline aluminium oxide was identified. A likely possibility, discussed more fully in a later section, is that the pyrophyllite contains aluminium additional to that shown in the classical formula: substituting for silicon in tetrahedral positions in the lattice, and as an hydroxylated cation in interlayer positions.

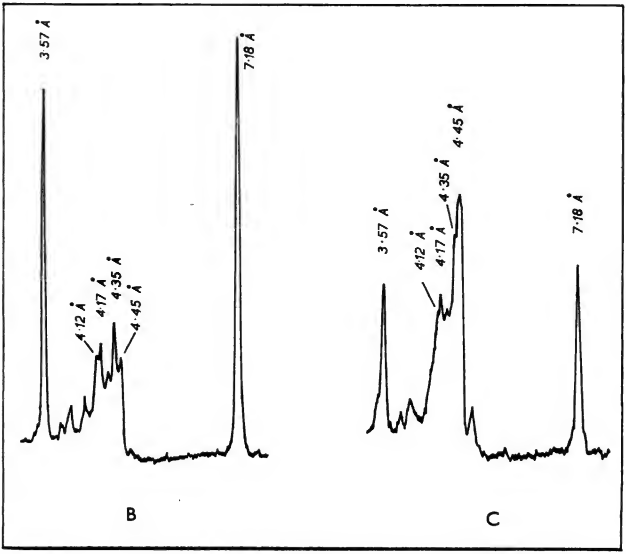


FIG. 2 (contd.). B—Representative sample from diaspore kaolin zone *A* showing resolution of kaolinite side spacings (4·0–4·5 Å). C—Representative sample from outer zone showing lack of resolution of kaolin mineral side spacings.

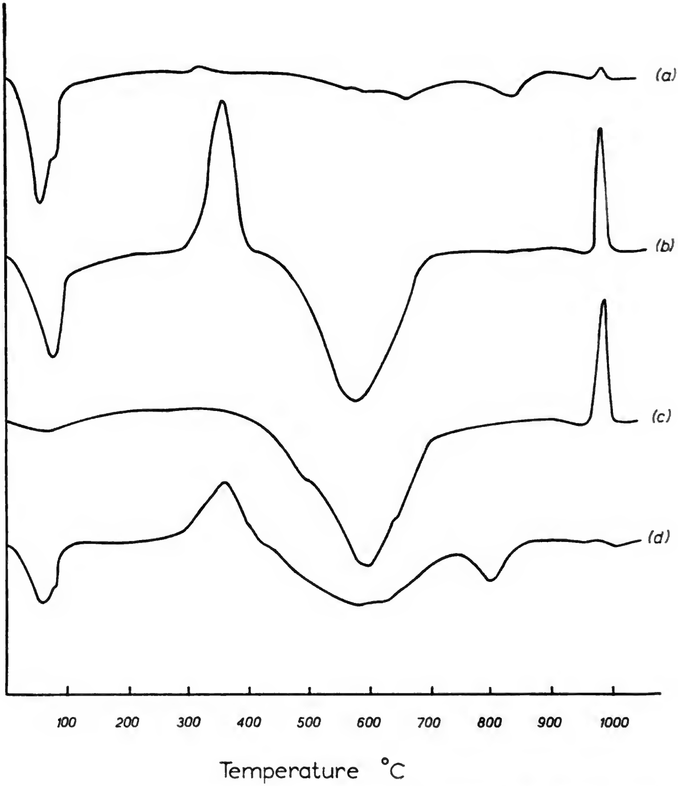


FIG. 3—Differential thermal analysis patterns. All samples Mg saturated and equilibrated at 56% relative humidity: (a)—Representative sample from pyrophyllite zone, showing pyrophyllite, kaolin, and pyrite; (b)—Clay fraction ($<2\ \mu$) of representative sample from pyrophyllite kaolin zone showing broad kaolin peaks; (c)—Representative sample from diaspore kaolin zone *A* showing kaolin, diaspore, and pyrophyllite; (d) Pyrophyllite; clay fraction ($<2\ \mu$) from pyrophyllite zone.

TABLE 3—Summarised Mineralogical Compositions of Parts and Zones of Pukepaukena

	Major Constituents	%	Minor Constituents	%	Other Constituents	Remarks
Western Part						
Zone						
quartz kaolin *A*	kaolinite	75	quartz	20	dickite, mica	very low in iron
quartz kaolin *B*	kaolinite	85	quartz	7	pyrophyllite, dickite, mica	very low in iron
pyrophyllite	pyrophyllite	80	quartz kaolinite	5 5	cristobalite, dickite, pyrite	excess Al_2O_3 and H_2O
pyrophyllite kaolin	kaolinite	70	pyrophyllite quartz	10 10	dickite, diaspore, feldspar, pyrite, etc.	good kaolinite by X-ray; broad endotherm in D.T.A.*
diaspore kaolin *A*	kaolinite	85	diaspore pyrophyllite	5–10 3–5	quartz, pyrite, dickite, feldspar	as for previous zone
diaspore kaolin *B*	kaolinite	90	diaspore	5	pyrophyllite, goethite, lepidocrocite, etc.	as for previous zone
diaspore - iron oxides - kaolin	kaolinite	80	goethite, lepidocrocite diaspore	10 5	sericite, epidote, zircon, etc.	
Eastern Part						
Sample						
63/110A	kaolinite	75	quartz	25		
63/110B	kaolinite	85	quartz dickite	10 5		
63/110C	kaolinite	55	quartz dickite	35 5–10	diaspore	best dickite sample
63/110D	kaolinite	90	quartz	5	dickite diaspore	
Quartz Band						
Sample						
63/108	quartz	95+	zircon			
63/109	quartz	95+	zircon			
Outer Zone						
Sample						
62/10–11	kaolin	50–60	montmorillonite, pyrophyllite	30–40		kaolin; probably halloysite
62/12	kaolin	60+	montmorillonite		pyrophyllite	kaolin; probably halloysite

*Differential thermogram

The $<2\ \mu$ fraction was separated from one sample and analysed separately. It was found to consist almost entirely of pyrophyllite. The chemical analysis of this fraction, shown in Table 2, corresponds to a composition of 90–95% pyrophyllite, with about 3% kaolinite, 1% goethite, and 1% quartz. Once again, more alumina and water than can be accommodated by classical formulae are shown by the chemical analysis.

Under the microscope, the pyrophyllite appears both as coarse irregular grains resting on the basal cleavage and as thin flexuose lamellae. Euhedral grains of zircon are common throughout.

Pyrophyllite Kaolin Zone—white clay with stones

This zone consists of 70% kaolinite, 10% each of pyrophyllite and quartz, and a smaller amount of pyrite. There are traces of feldspar, cristobalite, mica, dickite, and diaspore. The kaolinite endothermic peak in the differential thermogram (Fig. 3) is rather unusual in being exceptionally broad and shallow, and extends from about 400 to 700°C. The presence of pyrophyllite, with endothermic peaks which overlap the upper part of the kaolin endotherm, undoubtedly contributes to the broadness of the peak. The kaolinite exothermic peak at 980°C is sharp and clear.

In the chemical analysis (Table 1) the differences from the pyrophyllite zone (less silica, more alumina, and more water) are in line with the mineralogical results. There is also more iron oxide.

The clay fraction was analysed separately, and was found to consist of over 80% kaolinite, 5% pyrophyllite, 5% quartz, and 3% pyrite. A very large exothermic peak in the differential thermogram at 360°C is caused by the oxidation of pyrite. The kaolin endotherm in this fraction, like that of the whole sample, is broader than usual. The chemical analysis of the clay fraction, shown in Table 2, is very similar to that of the whole sample, shown in Table 1. The composition of the two must be very similar, although the sample contains only about 60% of clay. It is clear from this that the hard angular fragments in the sample have a similar composition to the clay matrix. Cementation is probably caused by amorphous silica or alumina.

Diaspore Kaolin Zone A—white cemented clay

Beside the pyrophyllite kaolin zone, which contains flat, cemented stones in a loose clay matrix, is a zone of hard, white, kaolin rock. Kaolinite comprises approximately 85% of the zone, and there is 5–10% diaspore, 3–5% pyrophyllite, small amounts of quartz and pyrite, and traces of dickite and feldspar. The X-ray diffraction pattern for sample 63/105 (Fig. 2) was obtained from a relatively unoriented powder sample, and the high resolution of the peaks between 4·5 and 4·0 Å, and again between 2·55 and 2·2 Å (not shown) is evidence for a well ordered kaolinite. In the differential thermogram of the same sample (Fig. 3) the main kaolinite endotherm is very broad and deep, like that of the kaolinite in the pyrophyllite kaolin zone. A minor peak on the descending line at 500°C is due to diaspore, and a second minor peak on the ascending limb at 650°C is thought to be due to pyrophyllite.

The $<2\ \mu$ fraction of a grab sample was analysed separately. A chemical analysis is shown in Table 2. The fraction consists of about 85% kaolinite, minor amounts of diaspore, pyrophyllite, and traces of pyrite, feldspar, and a zeolite.

A thin section cut from a hand specimen taken from this zone showed a matrix of very fine-grained, almost isotropic, clay with occasional patches of goethite and leucoxene, and grains of diaspore. The thin, colourless, flexuose lamellae of pyrophyllite occurred in patches and veins, usually surrounded by a thin skin of iron oxide, and usually showing local flow structures.

Diaspore Kaolin Zone B—green cemented porcellanic clay

This zone is distinguished from the previous one by its greenish colour, greater cementation, and the presence of veins bounded by iron oxides. The main analytical difference is that the green zone contains about 2½ times as much iron oxide as the white zone (*see* Table 1). The zone consists of 90% kaolinite, with the same very broad endothermic peak in the differential thermogram as in the pyrophyllite kaolin zone, and the first diaspore kaolin zone. Minor consituents are diaspore, goethite, dickite with traces of pyrophyllite, and mica. Lepidocrocite and goethite are found in the brown and black borders of the brighter green veins which run through the zone. The main constituent of such veins is kaolinite.

A thin section cut from a grab sample from the zone shows a fine-grained clay matrix with a degree of preferred orientation which suggests a shearing or flow structure. The matrix is stained and streaked with golden brown iron oxides. Occasional grains of diaspore, cristobalite, and zircon occur through the slide.

Diaspore Iron Oxides Kaolin Zone—brown-stained clay

The characteristic feature of this zone is that it retains some of the texture of the rock from which it was derived. It contains 80% kaolinite, 10% goethite and lepidocrocite, 5% diaspore, and traces of pyrophyllite, epidote, mica, and zeolite.

Veins of green kaolinite clay bounded by goethite and lepidocrocite run through the zone. A thin section cut from a hand specimen includes one of these green veins. The central part of the vein is composed mostly of colourless, fine-grained, unoriented clay, with small patches of pale yellow iron oxide occurring throughout. On the sides of the vein the clay is oriented. The iron oxides surrounding the vein seem to be derived from pyrite and show a consistent pattern of dark red interior, a red intermediate zone, and a brown to yellow outer zone, the colours probably representing different oxidation and hydration states. The vein probably represents a crack to which have migrated the iron oxides or pyrite in the altering rock. Later action, either hydrothermal or weathering, has caused kaolinite to fill the crack. Occasional laths of sericite occur, usually fractured and partly chloritised, and in some cases completely replaced by fine clay. Fine epidote is common in patches, and accessories include diaspore, cristobalite, and zircon.

The Eastern Part

Four grab samples of the white kaolin rock of the eastern part of Pukepaukena were taken from surface exposures. All four samples were mineralogically similar to the quartz kaolin zone of the western part (*see* Table 3). The main constituents of all four were kaolinite which ranged from 55–90% and quartz which ranged from 5–35%. Small amounts of dickite and diaspore were also found.

Siliceous Sinter

The band of siliceous sinter across the centre of the deposit consists almost entirely of quartz. Thin sections taken from two positions show dense arrangements of uniformly sized quartz crystals. Small euhedral crystals of zircon were very common throughout.

The Outer Zone

Two samples taken in and below a small bank some 70 ft north of the edge of the diaspore - iron oxides - kaolin zone, and a single auger sample, taken midway between these two and the edge of the diaspore - iron oxides - kaolin zone, were analysed. All three samples contain a kaolin mineral with a less well ordered structure than occurs in the previous zones. An X-ray diffraction pattern of the unoriented clay is shown in Fig. 2. The peaks between 4·5 and 4·0 Å are poorly resolved. Other major constituents are pyrophyllite and montmorillonite. The chemical analysis for one sample shown in Table 1 indicates that the montmorillonite is essentially aluminous.

GENESIS OF THE DEPOSIT

The andesites of Coromandel have been extensively altered, presumably at the time of emplacement of the gold and silver. The alteration has been studied by numerous workers, the most detailed work having been done by Finlayson (1909). In the most extensive type of alteration the ferromagnesian minerals were changed to carbonate, magnetite, and "chlorite". The chlorite was identified microscopically, and most of the material is probably montmorillonite. Where the alteration was more intensive, in the vicinity of veins of gold and silver, the original andesite was changed to a mixture of carbonates, sericite, quartz, pyrite, and magnetite. Dr A. Ewart (pers. comm.) has identified much montmorillonite by X-ray diffraction techniques in borehole samples from the Waihi mine. He found little evidence of chlorite.

The intensive alteration described in this present paper is not associated with the emplacement of gold or silver, and the hydrothermal solutions were clearly different from those which produce carbonates and sericite. Corroded grains of sericite and epidote occur in the diaspore - iron oxides - kaolin zone. Their presence suggests that regional hydrothermal alteration of lower intensity may have preceded the intense alteration which produced the pyrophyllite-kaolin-diaspore associations.

It seems reasonable to assume that the quartzite band marks the original fissure through which the hydrothermal solutions issued. As the activity decreased and the solutions cooled, quartz was deposited to fill the fissure.

The presence of pyrophyllite, dickite, and diaspore indicates that the deposits were originally formed deep in the earth under pressures and temperatures much higher than those that exist at the surface. Data from Roy and Osborne (1954) for diaspore and Carr (1963) for pyrophyllite show that the pressures must have been greater than 2,000 p.s.i., and the temperatures greater than 335°C.

The conversion of kaolin + quartz into pyrophyllite + water occurs only between 338°C and 450°C depending upon the pressure of water in the system and the activity of silica in the solution (Carr and Fyfe, 1960). High silica activities favour the formation of pyrophyllite. At low silica activities, kaolinite will be transformed into pyrophyllite and diaspore if the temperature is high enough. The former reaction has apparently occurred in the pyrophyllite and pyrophyllite kaolin zones, and the latter reaction in the kaolin diaspore zones.

In some of the zones pyrophyllite, kaolin, diaspore, and quartz are all present. The phase rule requires a fixed temperature and pressure for these four phases and water all to be in equilibrium. Fixed conditions are most unlikely in a hydrothermal situation, and it is more probable that variations in the activities of silica in the various zones have produced different mineral assemblages which have not then come into equilibrium with the final silica activities in the last stages of alteration.

Most of the inner zones are virtually free of iron oxides. Presumably the solutions contained sulphides which caused reducing and acid conditions. Some iron was precipitated as pyrite but most was swept out of the altering rock.

As hydrothermal activity waned, temperatures would fall and reactions between minerals cease in the zones away from the fissure. Nearer the fissure, however, solutions with high silica activities but lower temperatures probably would continue to pass and cause the pyrophyllite formed at higher temperatures to revert to kaolin and quartz. As the temperatures decreased further, silica in the solutions would be deposited in increasing amounts towards the fissure.

DETAILED EVIDENCE FOR UNCOMMON MINERALS

As a number of minerals are recorded here for only the first or second time in New Zealand it seems advisable to give more detailed descriptions of their properties.

Pyrophyllite

An X-ray diffraction pattern of a $<2\ \mu$ clay sample from the pyrophyllite zone is shown in Fig. 4. The sample is thought to contain 90–95% pyrophyllite, 10% kaolinite, and traces of oxides. The pattern was obtained with an unoriented powder sample using filtered CuKα radiation in a

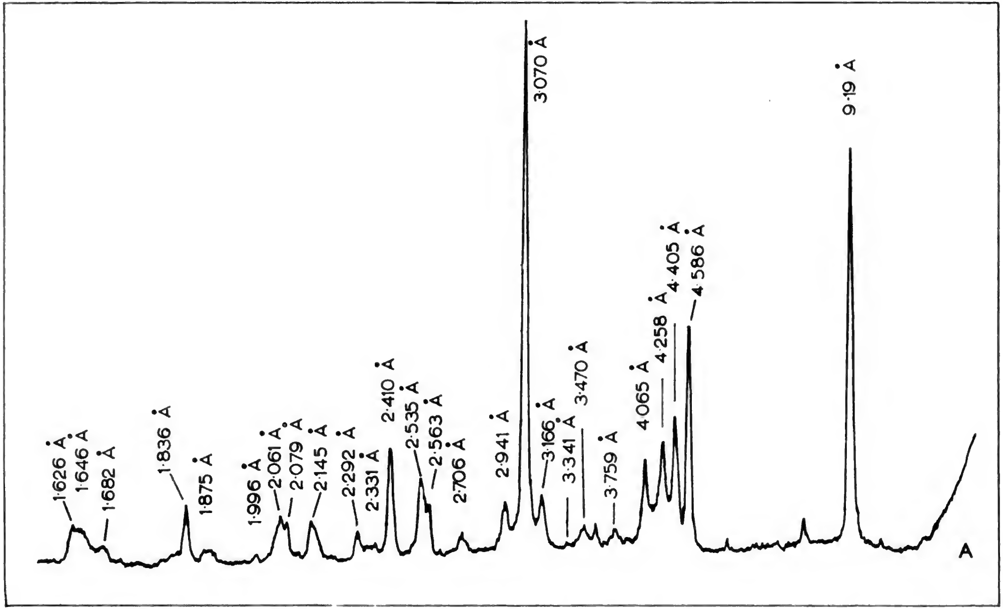


FIG. 4A—X-ray diffraction patterns of special minerals. Pyrophyllite; clay fraction ($<2\,\mu$) from pyrophyllite zone. Relatively unoriented powder sample.

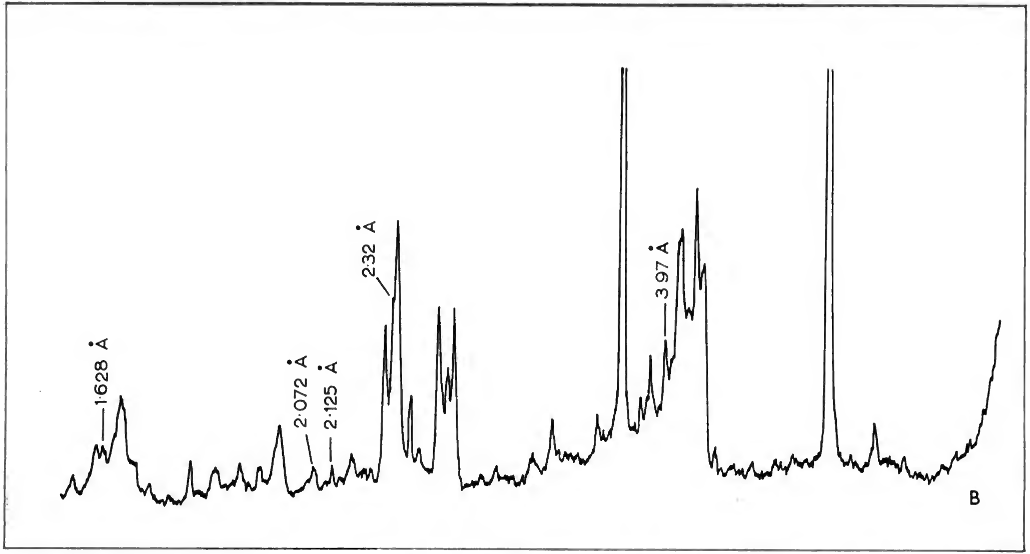
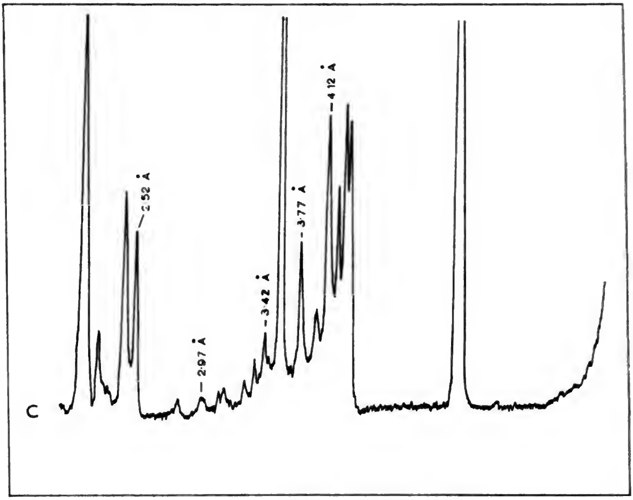


FIG. 4B—X-ray diffraction patterns of special minerals. Diaspore; representative, relatively unoriented sample from diaspore kaolin zone *A*; recorder set to emphasise diaspore peaks.



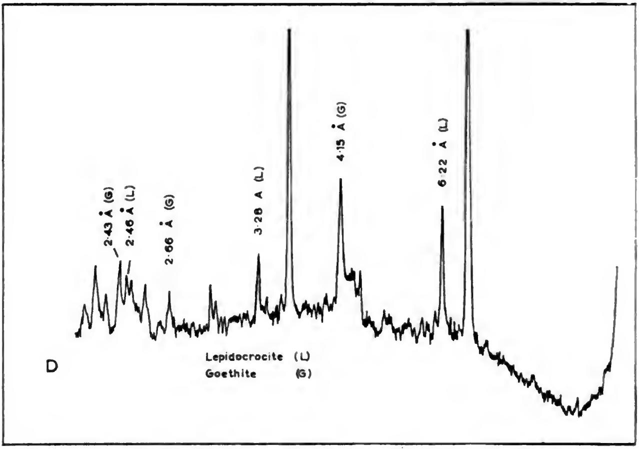


FIG. 4C—X-ray diffraction patterns of special minerals. Dickite; relatively unoriented powder sample from 5–2 μ fraction of 63/110C, eastern part of Pukepaukena; recorder set to emphasise dickite peaks.

FIG. 4D—X-ray diffraction patterns of special minerals. Lepidocrocite; sample from brown vein in diaspore iron oxides kaolin zone; recorder set to emphasise lepidocrocite peaks.

Philips X-ray diffractometer, at a scanning rate of ½° θ/minute, a time constant of 4 seconds, a count rate factor of 16, and a slit setting of 1°, 0·2°, and 1° for incident, receiving, and scatter slits respectively. The pyrophyllite peaks and their relative intensities are given in Table 4 together with the peaks and intensities for two pyrophyllite samples recorded in American Petrol. Inst. (1951) and Gruner (1934). The general correspondence is good, the most noticeable difference between this sample and the others being the presence of a strong reflection at 4·258 Å, which is not attributable to quartz.

The chemical analysis of the sample, shown in Table 2, confirms the absence of MgO from the mineral. When allowance is made for the small amounts of kaolinite and quartz in the sample, there seem to be small excesses of alumina and water, indicating some substitution of aluminium for silicon in tetrahedral positions. The calculated formula is

$$[\mathrm{Al\,(OH)_2}]^{+}_{0\cdot1}\,\mathrm{Al_2}\,[\mathrm{Si_{3\cdot90}\,Al_{0\cdot10}}]\,\mathrm{O_{9\cdot95}\,(OH)_{2\cdot10}}$$

A differential thermogram of the same <2 μ fraction is contained in Fig. 3. The sample was Mg saturated and equilibrated at 56% relative occur below 100°C and at 800°C. An exothermic peak at about 380°C is obscured by the broad endothermic trough of pyrophyllite which extends from about 500–700°C with a minimum at 600°C. Other endothermic peaks occur below 100°C and at 800°C. An exothermic peak at about 380°C is probably due to the oxidation of a small amount of pyrite in the sample.

replace

The mineral is optically negative, with parallel extinction, and gives good acute bisectrix figures. It has a refringence always greater than balsam, strong birefringence, and a 2V approximately 60°.

Morgan (1902) doubtfully identified pyrophyllite by its greasy feel in the Waihi mine and at Wharikirauponga, north of Waihi, but later (1927) decided that both records were doubtful and should be discarded. It seems that he may have been right the first time.

Dickite

Identification of small quantities of dickite in samples containing much kaolinite and smaller quantities of other minerals is difficult. It depends upon careful examination of the peaks occurring between 4·5 and 3·7 Å, and again between 2·8 and 2·0 Å. The peak occurring approximately at 3·42 Å is a fairly good indicator, provided it is possible to show that no zeolites occur in the samples.

The best example of dickite occurs in sample 63/110c, and an X-ray powder diffraction pattern over the significant region is shown in Fig. 4. The pattern was obtained from the 5–2 μ fraction of the sample, with

TABLE 4—X-Ray Powder Diffraction Data for Pyrophyllite

Tairua, N.Z.		After Robbins, N. C., *in* American Petrol. Inst. (1951)		After Gruner (1934)	
d(Å)	I	d(Å)	I	d(Å)	I
		9·39	2	......	
9·19	8·5	9·05	8	9·16	4
4·586	4	4·560	3	4·58	1·5
4·405	3	4·392	4	4·46	4
4·258	2·5	4·217*	6	......	
4·065	2	......	......	4·13	2·5B
3·759	<0·5	3·854	1	3·86	0·5B
3·470	0·5	......	......		
3·341*	<0·5	3·327*	10	3·35	3
3·166	1	3·117	2		
3·070	10	3·031	9	3·05	10
2·941	1				
2·706	<0·5B				
2·563	1				
2·535	2	2·540	6	2·529	2·5B
2·410	2·5	2·414	6	2·406	4B
2·331	0·5B				
2·292	0·5			2·292	2·5B
		2·278	3		
2·145	1	2·143	1	2·146	2B
2·079 2·061	1	2·075 2·072	1	2·075	1·5
		2·050	1	2·048	1·5
1·996	<0·5	1·988*	1		
1·875	<0·5	1·888	1	1·885	0·5
1·836	1	1·830	3	1·832	4
1·682	0·5B	1·663*	1		
1·646 1·626	1B	1·636	1	1·639 1·624	3 2

*Not assigned. B—Broad.

CuKα radiation, and a scanning speed of ½° θ/minute. Dickite is indicated by the 3·77, 3·42, and 2·97 Å peaks, by the greater intensity of the 4·12 over the 4·18 Å peak (not resolved) and by the relatively weak 2·52 Å peak.

Diaspore

Diaspore occurs as a minor constituent of many of the samples. It was positively identified by X-ray diffraction and by optical methods. An X-ray diffraction pattern of sample 63/105 is shown in Fig. 4. The pattern was obtained with a non-oriented powder sample, with filtered CuKα radiation, at a scanning rate of ½° θ/minute. The sensitivity of the recorder was set to bring out the diaspore peaks, and the peaks of the basal spacings of the kaolinite, which dominates the sample, were allowed to go off scale. The diaspore peaks are marked in the figure.

In the differential thermograms of samples 63/105, 63/106, and 63/107, small endothermic peaks at around 520°C on the descending limbs of the main kaolinite endotherm are thought to indicate diaspore.

Diaspore was identified in thin sections as wedge-shaped subhedral grains with very high relief and extreme birefringence. The grains were sometimes colourless and sometimes coloured, the latter showing a violet or lemon-yellow pleochroism.

The only previous discovery of diaspore in New Zealand was made microscopically by Hutton (1946) in river sands in a tributary of the Maungakirikiri Stream. The mineral had $\alpha = 1{\cdot}701 \pm 0{\cdot}003$, $\beta = 1{\cdot}721$, $\gamma = 1{\cdot}750$, $\gamma - \alpha = 0{\cdot}049$. It was optically positive, and had a 2V of approximately 85°. The locality is of particular interest because of the extensive deposits of siliceous sinter developed in propylitised andesite in the area.

Lepidocrocite

Lepidocrocite was identified by X-ray diffraction in the iron oxides surrounding veins in the diaspore kaolinite and diaspore - iron oxides - kaolin zones. An X-ray diffraction pattern is shown in Fig. 4, with the peaks of lepidocrocite marked. Goethite also is a constituent of the sample. The lepidocrocite has probably formed as an oxidation product of pyrite.

CONCLUSIONS

(1) Hydrothermal action has formed a deposit of clay, containing pyrophyllite, kaolinite, diaspore, and dickite, from andesitic rocks in the Coromandel area.

(2) The deposit is divided into western and eastern parts by a band of siliceous sinter thought to represent the central fissure.

(3) The western part is divided into seven zones. One zone contains over 80% pyrophyllite, and others are of kaolinite-dickite-quartz and kaolinite-diaspore.

(4) The eastern part, which is about an acre in area, consists of a varying mixture of kaolinite and quartz, with small amounts of dickite.

(5) The deposits were formed deep within the earth at pressures above 2,000 p.s.i. and temperatures above 335°C by waves of solutions with differing activities of soluble silica.

(6) The formula of the pyrophyllite minerals is

$$[\mathrm{Al\,(OH)_2}]^{+}_{0\cdot1}\,\mathrm{Al_2}\,[\mathrm{Si}_{3\cdot90}\,\mathrm{Al}_{0\cdot10}]\,\mathrm{O}_{9\cdot95}\,(\mathrm{OH})_{2\cdot10}$$

and the X-ray diffraction pattern and differential thermogram is similar to, but not identical with, patterns given in the literature. In particular this mineral had a strong X-ray reflection at 4·258 Å which could not be attributed to quartz.

(7) Dickite and lepidocrocite were identified in the deposits by their X-ray diffraction patterns. Diaspore was identified by its X-ray diffraction pattern, and under the petrographic microscope.

ACKNOWLEDGMENTS

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NOTES FROM THE NEW ZEALAND GEOLOGICAL SURVEY—5

NEW ZEALAND GEOLOGICAL SURVEY STAFF

Department of Scientific and Industrial Research

(Received for publication 22 July 1968)

INTRODUCTION

The sheet numbers (e.g., S62) of the grid references and sample numbers used throughout these notes are those of the 1:63,360 topographical map series (NZMS 1) published by the Department of Lands and Survey, Wellington. The co-ordinates that follow the sheet numbers are based on the New Zealand 1,000 yd grid printed on this map series. The same sheet numbers and grid are shown on the 1:63,360 and 1:250,000 geological maps published by the Department of Scientific and Industrial Research, Wellington.

The letters which prefix the New Zealand Geological Survey sample numbers used in these notes denote the following:

f —Fossil record number (preceded by sheet number);
F —Foraminiferal laboratory number;
GS—Macrofossil number;
L —Plant microfossil number;
P —Petrological laboratory number;
p —Petrological sample number (preceded by sheet number).

The numbers preceded by UCF are University of Canterbury fossil numbers.

NEW ZEALAND FOSSIL SEALS

A Tribute to the Work of the Late Dr J. A. Berry

C. A. FLEMING

Lower Hutt

Dr J. A. Berry (1890–1962), whose interest in many fields of geology and biology was noted by T. L. Grant-Taylor (1963), had devoted a considerable amount of time to the study of New Zealand fossil seal bones. After his death, a bulky carton of Dr Berry's papers and some specimens were deposited in the Geological Survey. Recently, when the papers were roughly sorted, the extent of Dr Berry's research was emphasised. Dr Berry's manuscripts are unfortunately not suitable for publication without review by an expert, but as fossil seals are rare and of high biological and paleontological interest, a summary is given below of the specimens on which he worked, and their localities.

N.Z. Jl Geol. Geophys. 11 : 1184–202

1. THE KIDNAPPERS MANDIBLE

This was described by Berry in 1928 as *Arctocephalus caninus* n.sp. Dr Berry later went to great trouble to localise the point of collection, and decided it was from the Opoitian sandstones immediately below the Black Reef Limestone, between Clifton and Cape Kidnappers, Hawke's Bay. He confirmed his original view that the fossil was closely related to Hooker's Sea Lion now living at the New Zealand Subantarctic Islands and consequently referred it to the genus (or subgenus) *Phocarctos*. It remains the geologically oldest fossil seal known from New Zealand. The type specimen is in the Dominion Museum.

2. THE NAPIER MANDIBLE

A complete mandible found embedded in limestone at Northe's Quarry, Faraday Street, Napier, was the subject of extensive comparisons because at first it seemed to Dr Berry to be a species of *Phoca,* a group of earless seals confined to the Northern Hemisphere (Harbour seals). Later, after correspondence and comparison overseas, he decided the Napier jaw was closely related to *Ommatophoca rossii* Gray, the Ross Seal of the Antarctic. As the Napier mandible comes from near the upper limit of *Phialopecten* at a horizon close to the Hautawan (Basal Pleistocene) where several cold water invertebrates occur in other parts of New Zealand, the occurrence of a seal related to the Ross Seal, now confined to Antarctic pack ice, is of very great interest. Dr Berry's identification as *Ommatophoca* was published by Fleming (1962, p. 85). The Napier mandible is in the New Zealand Geological Survey Office, Lower Hutt.

3. THE OHOPE SKULL

An almost complete skull of a sea lion from Ohope, presented to the Auckland Museum in 1939, was studied by Berry in great detail and compared with a large number of skulls in museums throughout the world. He eventually decided that the skull represented a new species of the genus *Neophoca,* as used in the restricted sense for the Australian Sea Lion, and thus an unexpected occurrence in New Zealand. The specimen came from the marine Castlecliffian (Putikian) beds at Ohope, near Whakatane, described by Fleming (1955). Casts of the skull are in the Geological Survey Office, Lower Hutt, and in the Dominion Museum.

4. THE WAIPUNGA FRAGMENTS

During the construction of the Hawke's Bay railway, workmen found what was apparently an almost complete seal skull in blue clay at a locality in central Hawke's Bay, variously described as "at Waikohou, about 20 miles from Napier", "blue clay at Kaiwaka", and "a mile or two beyond Waipunga in the direction of Mohaka", i.e., within a stretch of railway running through Nukumaruan beds (probably Upper Nukumaruan, Mr T. L. Grant-Taylor, pers. comm.), for about 8 miles north of Waipunga. In Dr Berry's words "an argument ensued as to whether the find was really a fossil skull or not and it was shattered to pieces with a pickaxe, when a number of two-rooted teeth were exposed". (Never, I think, was a paleontologist more restrained in his reference to a field collector's lack of care, though in this case a sense of personal tragedy must have persisted for the rest of Berry's life!) A few fragments were saved and sent to the late Mr Henry Hill, who passed them to Berry for examination.

There were five small fragments of various parts of the skull, one complete tooth and several fragments of teeth. Anyone but an expert on the cranial osteology of seals would have been daunted by these pathetic fragments, but Berry was indeed such an expert. He satisfied himself that the skull had belonged to an earless seal of the subfamily Cystophorinae, which includes the sea elephants (*Mirounga* or *Macrorhinus*) and the Northern Hemisphere Hooded Seal (*Cystophora*), but although *Mirounga* would not be unexpected in the New Zealand Lower Pleistocene, he was led to the conviction that the Waipunga fragments represent a new genus. He was well aware, however, that such fragmentary material was an unsatisfactory basis for describing a new genus, and his lengthy manuscript on the subject (unlike those on specimens 1 to 3 above), was not typed, so he probably decided not to publish. The fragments are now in the Geological Survey Office, Lower Hutt.

5. KAI-IWI VERTEBRAE

J. Park (1886) recorded that S. H. Drew collected four dorsal vertebrae of a seal from shell beds exposed in railway ballast pits near Kai-iwi, later classed in the Butler's Shell Conglomerate (Fleming, 1952, p. 175). A specimen later turned up at the Geological Survey consisting of three vertebrae, connected by concretionary siltstone, perhaps the same that Park referred to, although this is not certain. Hector had identified the vertebrae as *Arctocephalus "cinereus"*. Dr Berry confirmed (*in* Fleming 1962, p. 86) that they agree with *Arctocephalus forsteri* (the New Zealand Fur Seal, which is what Hector meant), but vertebrae are not the best bones for species determination. Fur Seals still breed in Cook Strait and probably extended further north in pre-human times, and there would be nothing strange in their occurrence in the Okehuan (Lower Pleistocene) of Wanganui district.

6. NINE-MILE BLUFF ISCHIUM

For completeness, we must add a broken bone found associated with fossil collection GS32, which consists mainly of Kaiatan marine mollusca from Nine-mile Bluff, north of Greymouth, collected by Hector in 1866, and A. McKay in 1873. The bone, however, is light and porous and obviously not contemporary with the mollusca. It was identified by Dr Berry as part of the ischium of *Hydrurga,* the Leopard Seal; it almost certainly came from a superficial deposit and is not fossil. Leopard seals stray occasionally to the New Zealand mainland.

As far as I know, the above list contains all the truly fossil seal remains so far known from New Zealand, but does not include "subfossil" specimens from caves, middens, and sand dunes.

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GRANITIC XENOLITH FROM MAYOR ISLAND

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Lower Hutt

INTRODUCTION

Mayor Island consists of Recent pantelleritic lavas and pumice deposits quite different from the calc-alkaline volcanic rocks of the Coromandel Peninsula, 16 miles to the west, and the Taupo Volcanic Region to the south (Ewart *et al.,* 1968). For this reason a granodioritic xenolith (P37288) recently found on the island by Mr D. E. H. Rishworth, New Zealand Geological Survey, Rotorua, is of interest and provides information on subsurface conditions in the region and may be compared with similar xenoliths from the Taupo Volcanic Zone (Ewart and Cole, 1967).

DESCRIPTION

The xenolith, subrounded in shape and approximately 12 cm in diameter, was found in a giant boulder of coarse pumice breccia at the northern end of Omapu Bay. The boulder had evidently fallen some 5 m from a cliff at the rear of the beach.

TABLE 1—Modal Analysis and Alkali Analysis of a Granitic Xenolith and Pantellerite from Mayor Island and a Granitic Xenolith from Hinuera, Taupo Volcanic Region

	1 (%)	2 (%)	3 (%)
Quartz	33·0	38·7	3·1
Plagioclase	17·7	17·5	......
Anorthoclase	......	......	9·2
Sanidine	40·9	42·5	......
Hypersthene	0·1	......	......
Hornblende	3·6	0·4	......
Aegirine	......	......	0·2
Biotite	4·3	0·6	......
Cossyrite	......	......	0·5
Magnetite Apatite Zircon	0·4	0·3	trace
Groundmass	......	......	87·0
K_2O	2·50	......	4·25
Na_2O	3·80	......	6·20

1. Granitic xenolith, Mayor Island, P37288. Alkali analysis by J. L. Hunt, N.Z. Geological Survey.
2. Granitic xenolith, Hinuera, Taupo Volcanic Region, No. 10923 of Victoria University Geology Department collection. (Ewart and Cole, 1967.)
3. Pantellerite lava, Mayor Island, P29537. (Ewart *et al.*, 1968).

The rock has an average grain size of about 2 mm, and is characterised by well developed graphic intergrowths of quartz and sanidine. Both minerals also form discrete crystals, the sanidine being interstitial to plagioclase and the intergrowth areas. The sanidine, composition Or_{64} by the X-ray method (Orville, 1963), has a cloudy appearance because of abundant minute glassy inclusions, and rare, poorly developed microperthitic texture.

Euhedral to subhedral plagioclase, An_{18}–An_{26}, occurs in crystals up to 2·5 mm long with normal and oscillatory zoning and occasionally with patchy zones in cores.

The biotite and green hornblende are present both as small, isolated anhedral grains and as larger crystals (the hornblende up to 5 mm long), in places often forming intergrowths with hypersthene. The xenolith is partly covered by a thin, irregular coating of pale orange-brown clinoptilolite apparently formed from the devitrification of a glassy skin.

CONCLUSIONS

In mineralogy, texture, and alkali content the Mayor Island xenolith is remarkably similar to xenoliths from the Taupo Volcanic Region (Table 1), especially those with extensive graphic intergrowths from Atiamuri and Hinuera (Ewart and Cole, 1967). These xenoliths have many features in common with the acid volcanic rocks of the region. However, the Mayor Island xenolith (Table 1) is mineralogically and chemically different from the pantellerites and therefore cannot be co-magmatic with them. A plutonic equivalent to the pantellerites would be an alkali granite of sodic mineralogy such as the many ejected alkali granite blocks associated with the pantellerites of Ascension Island (Tilley, 1951). These blocks invariably contain alkali pyroxenes or amphiboles and are regarded as co-magmatic with the lavas (Tilley, 1951; Roedder and Coombs, 1967).

Another possible explanation is that the xenolith was co-magmatic with earlier calc-alkaline eruptions on the Coromandel Peninsula or beneath present sea level, or at Mayor Island itself. There is no evidence, however, of early calc-alkaline eruptions on Mayor Island and the volcanic inclusions there are of alkaline affinities (Ewart *et al.,* 1968).

The most probable explanation is that the xenolith represents accidentally included basement material modified and ejected during a pyroclastic eruption. Rapid heating and cooling of the xenolith during and after the eruption would result in the formation of sanidine from orthoclase or microcline (e.g., Goldsmith and Laves, 1954), and partial melting could produce the extensive graphic intergrowths of quartz and sanidine which characterise the rock.

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AGE OF ROTOITI BRECCIA

B. N. THOMPSON

Papatoetoe

Rotoiti Breccia forms a submaturely dissected plateau sloping down northwards from the Okataina Rhyolite Centre (Thompson, 1964; Healy, 1964), which lies between Lakes Rotorua and Rotoma. Terrace deposits (H_{2+1}), correlated with the Last Glaciation (Upper Pleistocene), abut the northern margin of the plateau (Healy, Schofield, Thompson, 1964).

The general sequence in the area is shown in Table 2.

TABLE 2—General Sequence in the Area between Lakes Rotorua and Rotoma

Thickness (ft)	Lithology	Formation
<15	Brown, volcanic ash.	Rotorua Sub-group
160	Loosely compacted pumice breccia and interstratified airfall ash beds.	Rotoiti Breccia
<30	Fine grained tuffaceous siltstone consisting of layers of pumice and ignimbrite fragments; some layers contain tree trunks, twigs, and carbonaceous beds. Forms basal part of Rotoiti Breccia.	
<5	Brown clay, probably weathered surface of Mamaku Ignimbrite.	Mamaku Ignimbrite
300	Soft, pink ignimbrite containing abundant lumps of devitrified pumice up to 1 in. diameter in a slightly fused matrix that becomes harder with depth.	

The breccia is almost everywhere overlain by Rotorua Sub-group volcanic ash fall, of which the oldest named bed at Tikitere Hill, near Lake Rotorua, is the undated Rerewhakaaitu Ash (Healy *et al.*, 1964, table 3). The surface of the breccia is dissected by streams that have cut through to Matahina Ignimbrite on the east side of the plateau and to Mamaku Ignimbrite on the west side.

Sample N67/506 was collected from a section of the basal siltstone member of Rotoiti Breccia exposed in the roof of an exploratory drive beside a stream at N67/826235 near the Kaituna River (*see* Table 3).

Carbonised wood has also been cored from the base, middle, and top of the basal siltstone member of Rotoiti Breccia in six holes drilled close to the Kaituna River.

The radiocarbon sample (N67/506) yielded a result of >41,000 yr, 67% probability (NZ C^{14} 643).

This sample is from near the top of the basal siltstone member that was buried by a thick deposit of loosely compacted pumice breccia, and it gives an indication of the age of the first pumice avalanches to reach the middle portion of the Kaituna River. Because the surface of Rotoiti Breccia rises to the northern margin of the Okataina Rhyolite Centre, the breccia is thought to have been erupted from vents in this area, and as many of the rhyolite domes and the eroded surface of Rotoiti Breccia are mantled only by Rotorua Sub-group ash, the breccia and the domes are of approximately the same age. The lower members of the breccia may have been erupted during the early stages of formation of these domes. Therefore, because this age is quoted as older than 41,000 yr, it indicates a minimum age for commencement of rhyolitic volcanism in Okataina Rhyolite Centre.

My thanks are expressed to the Institute of Nuclear Sciences for the age determination.

TABLE 3—Sequence of Rotoiti Breccia and Mamaku Ignimbrite Beds Exposed at N67/826235

Thickness (in.)	Lithology	Formation
	Roof of drive.	
6	Soft white pumice lumps up to ¼ in. diameter. Lower 3 in. pumice stained brown.	Rotoiti Breccia
6	Wood (N67/506), some with bark preserved covering darkened trunk, some soft, spongy, and charred, in a black silt grade matrix.	
15	Black silt above grades into a light grey, clayey, moderately hard siltstone, of ignimbrite fragments, enclosing fragments of wood.	
1½	Brown stained, banded, light and dark coloured fairly hard siltstone of ignimbrite fragments.	
9	Off-white coloured, fairly hard siltstone, of ignimbrite fragments, containing scattered fragments of wood.	
	Grades into:	
30	Brown clay—probably weathered top of Mamaku Ignimbrite.	Mamaku Ignimbrite
18	Pink ignimbrite.	
	Floor of drive.	

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EXPERIMENTAL CRYSTALLISATION OF A LAMPROPHYRE GLASS

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Greymouth

INTRODUCTION

During a petrological study of the lamprophyre dike swarm in the lower Buller Valley (Nathan, 1966) several experiments were made to test the effects of melting and recrystallising a typical specimen. Unfortunately, time has not allowed an exhaustive experimental programme to be carried out or the problems raised by the present work to be further investigated, but as the writer is unable to continue the experiments at this time the results are presented for the information of other petrologists.

The lamprophyres in the lower Buller Valley are porphyritic hornblende monchiquites, rather variable in chemical composition (in part due to varying degrees of alteration) but mineralogically uniform (Nathan, 1966, pp. 157–84). An analysis of the specimen selected for experimental work (UC5196) is presented in Table 4 (col. 1). If considered on a dry, CO_2-free basis (col. 2), UC5196 differs mainly from Nockolds' average alkali basalt (col. 3) in containing 4·3% less SiO_2 and 2·9% more total $FeO + Fe_2O_3$.

TABLE 4—Chemical Analyses of a Lamprophyre from the Lower Buller Valley and Nockolds' Average Alkali Basalt

	1	2	3
SiO_2	37·7	42·5	46·77
Al_2O_3	13·2	14·9	14·65
Fe_2O_3	3·7	4·2	3·71
FeO	9·2	10·4	7·96
MgO	6·8	7·7	6·82
TiO_2	3·3	3·7	3·00
MnO	0·13	0·15	0·15
CaO	9·5	10·7	12·42
K_2O	1·80	2·03	1·07
Na_2O	2·45	2·77	2·59
P_2O_5	0·72	0·81	
CO_2	5·4		
H_2O+	1·20		0·51
H_2O-	4·15		
Total	99·09		

Molecular Norms

	1	2	3
Ap	2·0	1·7	0·8
Il	4·8	5·3	4·4
Cc	14·4	......	......
Or	11·0	11·2	6·5
Ab	23·5	9·2	21·5
An	21·0	22·6	25·5
Mt	4·0	4·6	3·9
Di	3·6	22·0	27·6
Hy	6·0	......	......
Fo	9·6	13·1	8·1
Ne	......	10·2	1·5

1. Lamprophyre (UC5196): Dike in Coulter Creek about ½ mile upstream from its junction with Stable Creek (S31/213614). Unpublished analysis by the Chemistry Division, DSIR, 1965.
2. Analysis I recalculated free of H_2O+, H_2O-, and CO_2.
3. Average alkali basalt (Nockolds, 1954).

Experimental Procedure

Sample Preparation

The rock was crushed in a steel mortar, to pass through a 200-mesh sieve and then dried for 8 hours at 110°C to remove all free water (H_2O-). Small samples, each weighing approximately 0·4 gm, were then fused to glass by holding them in a carbon arc for 15 sec which was found by experiment to be the minimum fusion time in which a homogeneous glass containing no relict crystals could be obtained. The glass beads were wrapped in platinum foil and placed in the "hot spot" of an electrically heated muffle furnace. All runs were started at 1,300°C, and the temperature was then lowered rapidly (over 5 min or less) to the desired level. Temperature control was ±5°C, and all runs were made twice. At the end of a run the sample was removed from the furnace and placed on a cool table. Air cooling chilled the samples very rapidly, and they could be handled less than 30 sec after removal from the furnace.

Identification of Products

Small portions of each sample were crushed and examined in oils, and thin sections of most specimens were also prepared. The phases observed are similar to those described and figured by Yoder and Tilley (1962). Clinopyroxene appears as elongate grains (parallel to the *c*-axis) which have dome or pyramid terminations and the characteristic inclined extinction. Skeletal forms (as illustrated in Fig. 1C) are common. Most grains of clinopyroxene are coloured very light yellow but a very few have a deeper yellow-brown colouration which may indicate the presence of the Fe^{+++} ion (Deer *et al.,* 1966; Yoder and Tilley, 1962). The iron oxides appear in a variety of octahedral and skeletal cubic forms (Fig. 1C and D). Dr K. R. Gill (N.Z. Geological Survey) examined a specimen under reflected light and reported: "The opaque minerals are all magnetite; at magnifications up to 1,050× in oil immersion there are no indications of the high reflectivity and anisotropic phases that might be haematite or other oxides. All crystals, regardless of size, are homogeneous, isotropic, and have the right colour and reflectivity for magnetite; I think that you are justified in assuming that this is the only opaque phase present. There is a possibility that the magnetite is a titaniferous variety, but this cannot be proved by optical examination alone. The majority of the magnetites either have three or four fold symmetry, and many of them contain glass inclusions symmetrically arranged." There is a large variation in grain size of both clinopyroxene and magnetite—about a factor of 100 is a reasonable guess. No other crystalline phases were noted in any of the products. Glass is light orange-brown under plane polarised light and completely isotropic under crossed polars.

Oxidation During Runs

One of the main problems of conducting high temperature experimental work in air is the possible oxidation of ferrous to ferric iron, with the consequent precipitation of excess iron oxides and the depletion of the melt in FeO. Green and Ringwood (1966, pp. 137–8) noted the severe oxidation effects after heating a crushed basalt powder to 800°C for several hours.

For this reason no attempt was made to remove H_2O+ and CO_2 by prolonged heating during sample preparation as it was thought that they should diffuse rapidly from the sample during fusion and during the runs. The vesicularity of the products from most runs appears to support this assumption, but future experiments should aim to start with a completely water-free and volatile-free sample.

Yoder and Tilley (1962) discussed the problem of making runs in air at atmospheric pressure on basaltic samples, and concluded that a run length of 1 hour was adequate to attain equilibrium while at the same time minimising oxidation. The light yellow colouration of clinopyroxene crystals indicates that the presence of the ferric ion, and two of the runs contained an excessive amount of magnetite; however, the complete absence of phases such as haematite or pseudobrookite suggests that oxidation was minor. One of the runs containing excessive magnetite was repeated for a shorter period (see below).

Experimental Results

The results of crystallising the lamprophyre glass at temperatures between 1,100°C and 1,300°C are summarised in Table 5. Most of the glassy products were vesicular, and there was a wide range of crystal size, with the largest grains usually in the centre of the charge (Fig. 1A). The crystals clearly have the form of primary rather than quench phases (cf. Yoder and Tilley, 1962, plate 5, no. 2, 3), and their size distribution may be caused by a slight heat gradient between the centre and outside of the glass globules. The two runs at 1,150°C and 1,100°C (no. 1 and 3) gave charges with such a high percentage of magnetite that it was almost impossible to see the other phases in transmitted light. Run 1 (1,100°C) was repeated for only 20 min; in this case the charge contained only about 25% of crystals, and was very similar to the products formed in runs at higher temperatures.

FIG. 1A–D—Photomicrographs of the products formed by the experimental crystallisation of a lamprophyre glass.

A (Upper left)—A typical globule under plane polarised light, showing the vesicular nature of the product and the variation in grain size. ×55.

M. Shelley, photo

B (Upper right)—Detail of Fig. 1A, showing the shape and texture of the hornblende and magnetite crystals. × 270.

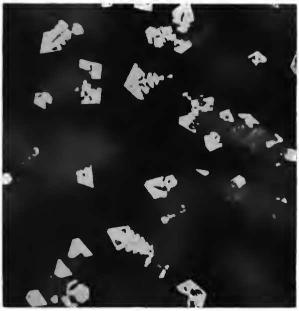
M. Shelley, photo

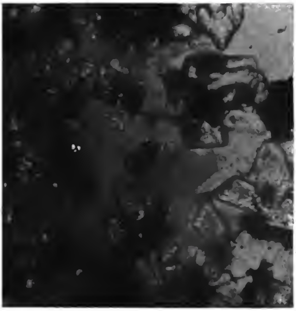
C (Lower left)—Polished section of a globule under reflected light, showing the typical skeletal form of pyroxene and magnetic crystals. Oil immersion, × 425.

S. N. Beatus, photo

D (Lower right)—Detail of Fig. 1C, showing a single symmetrical skeletal magnetite crystal. Oil immersion, × 1,025.

S. N. Beatus, photo





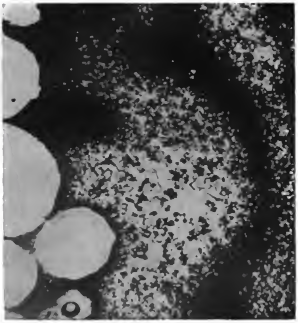


TABLE 5— Products Formed during the Experimental Crystallisation of a Lamprophyre Glass

Run Number	Temperature (°C)	Time (minutes)	Products*	Comments
7	1,300	60	Gl	
4	1,250	60	Mt + Gl	
2	1,200	60	Mt + Cpx + Gl	
5	1,175	60	Mt + Cpx + Gl	
3	1,150	60	Mt + Cpx + Gl	Charge almost opaque due to finely disseminated magnetite
1	1,100	60	Mt + Cpx + Gl	
6	1,100	20	Mt + Cpx + Gl	

*Abbreviations are the same as those used by Yoder and Tilley (1962).

DISCUSSION

Apart from the absence of hornblende and analcime (which would not be expected to crystallise under anhydrous conditions), the minerals identified in the globules are similar to those found in the parent lamprophyre, and plagioclase is consistently absent. Several writers (e.g., Vincent, 1953; Ramsay, 1955; Challis, 1960) have suggested that the distinctive mineralogy of many lamprophyres is caused by the crystallisation of alkali basalt under marked water vapour pressure, and the experiments under "wet" conditions by Yoder and Tilley (1962) appeared to bear this out. However, Yoder and Tilley (1962) demonstrated that all the Hawaiian basalts crystallised by them project close to the four-phase curve in the simple system Ab–An–Di–Fo, which suggests that other primitive basalts (i.e., those unmodified by differentiation processes) should behave similarly. In the present case the fact that the plagioclase liquidus has not been reached by 1,100°C suggests strongly that the composition of UC5196 does not project close to the four-phase curve, and is therefore rather different from most ordinary basalts. Although the results of a small set of experimental runs on a single specimen must be treated with some caution, present evidence indicates that the hornblende monchiquites in the lower Buller Valley are derived from a distinct lamprophyre magma, and not by the hydrous crystallisation of basalt magma.

Professor D. S. Coombs (University of Otago), Drs D. Shelley and J. B. Stott (University of Canterbury), Dr K. R. Gill (formerly of the New Zealand Geological Survey), and the technical staff of the Geology Department, University of Canterbury, are thanked for assistance in carrying out this project and in preparing the manuscript.

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ALUNITE AT KUAOTUNU, COROMANDEL PENINSULA

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Papatoetoe

INTRODUCTION

Alunite has been noted as a common member of hydrothermal assemblages resulting from the epigene sulphuric acid alteration of acidic volcanic rocks (Steiner, 1953, 1963; Harvey, 1967). Although alunite is not uncommon in sinter deposits at Whitianga (Harvey, 1967) and in silicified andesite at Thames (Hutton, 1947), this is the first occurrence for the Coromandel Peninsula where the alunite occurs in silicified greywacke.

Locality and Geological Setting

The sample was collected from the bleached and silicified contact zone exposed above the road between Kuaotunu and Otama on the north side of Black Jack (N40/233776), a peak formed by a pipe of siliceous sinter intruding Manaia Hill lithic volcanic greywacke at the north end of Waitaia Ridge (Schofield, 1967). The boundary between sinter and greywacke is diffuse, but the contact is even more obscure as a result of weathering and leaching. Veins of comb quartz containing pyrite and platy marcasite cut Manaia Hill Group beyond the alteration zone and sinterous material from the cliff below the alunite locality contains scattered cubes and dark grey lenses of finely divided pyrite.

Alunitised Rock

The material in the zone of alteration ranges from a hard grey-white, silicified rock (density 2·58) to a porous, pink alunite-quartz aggregate (density 2·51). The silicified material includes patches of kaolin up to 0·5 mm in diameter and has veinlets and box-works of limonite filling joints although no sulphide mineral appears to have been present within the rock itself. In contrast, the alunite-rich material contains nests and scattered crystals of pyrite and has "veins" of kaolin up to 5 mm thick lining its joints.

In thin section, the silicified rock has a microgranular texture of quartz with scattered flakes of alunite less than 0·02 mm in length, whereas coarser, porous, alunite-rich material consists of approximately 75% alunite, with minor interstitial micro-granular quartz, crystalline quartz lining small geodes, irregularly developed pyrite grains, and clay.

ALUNITE

The alunite crystals are well developed prismatic laths less than 0·2 mm in length in random orientation and intergrowth. The cores of many of the crystals are missing as though the alunite has been internally replaced by, or has itself replaced some mineral that has since been leached out.

Refractive indices (±0·002) are $n_\omega = 1{\cdot}570$ and $n_e = 1{\cdot}590$. They indicate a potash alunite with a negligible soda content (Larsen and Berman, 1934). The X-ray diffraction pattern (Table 6) is also much closer to a potash alunite, except that well developed peaks at 2·88 Å and 1·92 Å are somewhat inconsistent with both the standard K-alunite and the standard Na-alunite; optical inspection confirmed that the X-rayed sample contained nothing but alunite and minor quartz.

TABLE 6—X-ray Diffraction Patterns for Alunite

K Alunite A.S.T.M. 1–0879		Kuaotunu Sample		Na, K, Alunite A.S.T.M. 4–0865	
dÅ	I/I′	dÅ	I/I′	dÅ	I/I′
5·71	25	5·71	w	5·76	10
4·94	50	4·92	s	4·99	20
3·49	40	3·54 3·46	w–vw	3·51	30
				3·24	10 (broad)
2·98	100	2·97	vvs	3·01	85
2·88	5	2·88	vvs	2·90	20
2·47	10	2·45	w	2·48	20
2·29	50	2·29	s	2·29	75
2·20	20	2·23 2·20	vw	2·26 2·21	30 10
		1·92	s		
1·89	60	1·90	m	1·90	100
1·74	50	1·75	w	1·75	90
		visually estimated intensities			

The density measurements of four sinter samples were made in 1965 by Mr A. E. Leopard, Geophysics Division, Department of Scientific and Industrial Research, Wellington.

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SIMMONDS ISLAND, HENDERSON BAY, NORTHLAND (N4)

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Papatoetoe

INTRODUCTION

Simmonds Island (N4/652121) lies just over 1 mile off shore in Henderson Bay, 1,000 yd due north of Grenville Point (Fig. 2). As a preliminary to the possible reservation and declaration of the island as a Wildlife Reserve, it was examined for evidence of mineralisation by Mr H. E. Rowe, Inspector of Mines, Auckland, and the author. Most of the time spent on the island was devoted to a search for minerals, but brief geological notes were made and samples collected for petrological examination. The petrological determinations were carried out by Dr G. A. Challis, New Zealand Geological Survey, Lower Hutt. Sample localities are shown on the map (Fig. 2) by the appropriate record sheet numbers.

The only practical landing place, which is not without difficulty even in a calm sea, is in a small rocky embayment on the south-east side of the island, to the west of Anapuhipuhi Blowhole. The approximate route followed during the examination of the island is shown on the map. Those parts of the coast not reached by land were examined with field glasses during a circumnavigation of the island.

PHYSIOGRAPHY

Simmonds Island is traversed by many north-west striking shear zones. Shear-controlled erosion has produced long, narrow indentations that are particularly marked along the northern coast, and a narrow strip of rock and sand produced in this manner, which may be awash at high tide and must certainly be so in even a moderate storm, divides the island into two hills, here called West Hill and East Hill (Fig. 2). Two similar channels, containing at least 6 ft of water at low tide, separate two much smaller islands off the west coast of Simmonds Island. A third small island lies 400 yd north of the northern coast.

East Hill rises fairly gently to nearly 100 ft above sea level so that the frequent and good exposures of rock on the relatively bare slopes are easily accessible. Anapuhipuhi Blowhole spouted thick clouds of spray even in the calm conditions prevailing during the examination of the island. West Hill rises to nearly 150 ft above sea level with a steep face along the southern coast. A rock platform is exposed at low tide. The indented channels along the north coast impede travel, as does the thick growth of native shrubs on the higher parts of the hill. The two small western islands both rise steeply from the sea, or, at the northern end of the outermost island, from a rock platform that is submerged at high tide.

The small island 400 yd to the north of Simmonds Island barely merits the name, much of it being submerged at high tide.

GEOLOGY

The bulk of the island is made up of much-sheared, quartz-veined interlayered argillites and basalts that are often difficult to distinguish from each other in hand specimen. Locally, the argillite is quartzitic and may approach quartzite in composition. Breccia is found in some localities; one sample from the northern part of the island (p543; P36547) consists of brecciated chert with fragments of fine-grained, igneous rock. In places, the contact between obvious basalt flows and the interbedded argillite and basalt sequence is quite prominent. One such contact on the north side of West Hill has an irregular strike about 090° and dips about 35° N; another on the western side of East Hill has a strike and dip of 177° W and 25° W respectively, more or less parallel to the underlying interbedded argillite and basalt. No pillow lavas were seen. All basalts collected are medium to fine grained and composed of a felted network of feldspar microlites, granular augite, epidote, chlorite, and much dusty magnetite (p542; P36546). Fine quartz veins are common (p542; P36546) and are sometimes accompanied by fine veins of albite (p546; P36550: p547; P36551). Locally the feldspar microlites show strong flow alignment (p547; P36551). At the top of East Hill a light, creamy-coloured, very fine-grained rock (p544; P36548), consisting of an interlocking network of quartz and feldpsar with microlites of ?augite showing skeletal growth, could be an altered, devitrified, glassy rhyolite, or keratophyre.

Dikes intruding the argillite-basalt sequence include one, 2–3 ft thick, of albite dolerite (p541; P36545) that strikes 122°–127° across the south-western side of East Hill and dips 80° north-east. It consists of microphenocrysts of scarce feldspar and rare augite in a very fine-grained matrix of feldspar microlites and tiny prisms of brown hornblende. The feldspar is mainly albite, which also fills circular varioles. This dike cuts across, and offsets by 2 ft, a 4-ft-thick dolerite dike (p545; P36549) that strikes 252° down the south-western side of the hill and dips 80° north. What is presumed to be the same dike is exposed on the east side of West Hill, but offset clockwise by some 70 ft at the strongly sheared zone that separates the two hills. It is composed of a fine-grained matrix of completely altered feldspar and chlorite with scarce, large, augite prisms and smaller, greenish brown, hornblende prisms. The texture and mineralogy of the rock is not

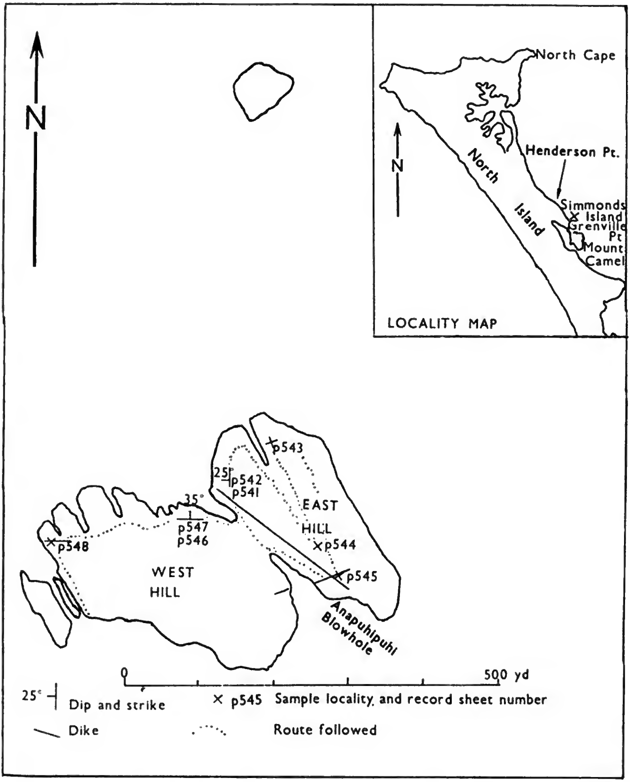

FIG. 2—Sketch map of Simmonds Island (N4).

unlike that of a camptonite. Another dike (p548; P36552, P36553), 2 ft thick, strikes 094° across the western coast of the island, and dips 85° north. It also resembles a camptonite.

These rocks have been shown as part of the Cretaceous Mount Camel Volcanics (Kear and Hay, 1961) and closely resemble such rocks exposed on the mainland, in particular the quartzitic argillites, interbedded with volcanics and cut by albitised dolerite dikes, exposed in the vicinity of Grenville Point. They are therefore correlated with that formation.

MINERALISATION

The only mineralisation seen on the island consists of thin discontinuous coatings of limonite along joints and shears. This is quite clearly of no economic interest.

KEAR, D.; HAY, R. F. 1961: Sheet 1—North Cape. "Geological Map of New Zealand, 1:250,000." Department of Scientific and Industrial Research, Wellington, New Zealand.

BASALT DIKES IN THE TARAWERA VOLCANIC COMPLEX, NEW ZEALAND

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(Received for publication 26 March 1968)

Abstract

Magnetic and geological measurements indicate that a basalt dike occupies the fissure formed during the 1886 eruption in the Tarawera Volcanic Complex, and is confined to the Complex. Parallel to this dike, but 300 yd to the south-east, lies a second dike which is not visible at the surface.

Introduction

The Tarawera Volcanic Complex lies 15 miles south-east of Rotorua, and forms the southern margin of the Okataina Volcanic Centre (Healy, 1962). It consists of 12 rhyolite domes and plugs, the most recent of which (Tarawera, Ruawahia, and Wahanga) were formed in about A.D. 1020 (Cole, 1965). The last activity was on 10 June 1886, when an explosive eruption of basalt occurred from a series of craters along a north-east fissure across the Complex. This fissure, which is over 500 ft deep in places and up to 300 ft wide, extends 9 miles from Wahanga Dome to Haumi Valley (Fig. 1), and includes part of the area now covered by Lake Rotomahana. The fissure has been mapped (Healy *et al.*, 1964) as lying on a fault.

Watson-Munro (1938) made magnetic (vertical force) measurements across the fissure which showed that "the bulk of the distribution of the basic material is clearly at the Tarawera end of the rift", and that little was associated with the fissure to the south-west. He did not recognise that a dike cropped out, but concluded that "the basalt had welled up close to the surface along the rift during the eruption".

Geological Observations

In a crater on the south side of Wahanga Dome a small basalt dike containing large numbers of highly vesicular and partly remelted rhyolite blocks is exposed (Fig. 1). It is approximately 3 ft wide with a chilled margin on either side, and probably represents a feeder for the first part of the 1886 eruption. The dike can be traced at this locality for a distance of only 20 ft, but it can be found again to the south-west of Ruawahia Trig (N77/963928*) where the eruptive fissure is about 30 ft wide, and the dike has a more complex form. Contact between the molten dike and the rhyolite

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*Grid reference based on the sheet district of the 1 : 63,360 topographical map series (NZMS 1) and the national thousand-yard grid shown on this series.

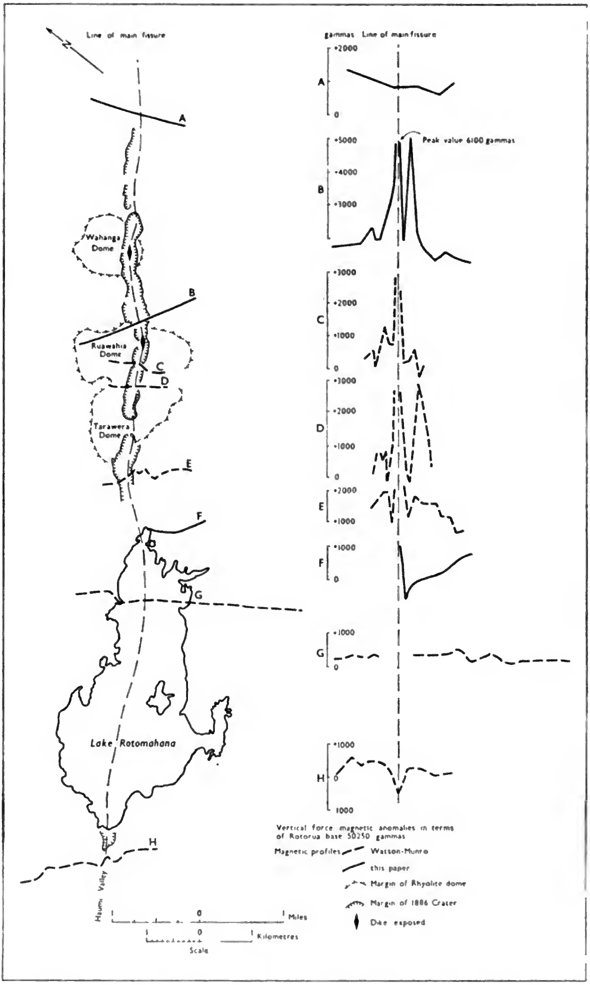

Fig. 1—Vertical force magnetic anomaly profiles across the Tarawera Volcanic Complex. (Peak values of Watson-Munro's traverse not determined.)

wall appears to have chilled the dike and at the same time remelted the rhyolite to form glass. Towards the cross-sectional centre a series of vertical layers can be identified, each chilled against the previous one and becoming more vesicular toward the centre. This could represent a multiple dike, but since basalt covers the rhyolite on each side of the fissure above the dike, it seems more likely that the lava was splashed up the sides of the fissure and then flowed back into it a short distance before cooling. This is comparable to some eruptions witnessed in Hawaii.

Between the two outcrops of the dike described, there is no massive basalt visible at the surface. There are two possible reasons for this. Firstly, there may have been a change in the type of activity at the north-east end of the fissure during the eruption. Rhyolite surrounding the eruptive fissure may have collapsed inwards causing a temporary blockage of some of the vents. The resultant violent explosions in clearing the debris would also destroy the top of any early formed dike. At the south-west end of Tarawera this violent activity apparently did not occur since the sides of the craters are still coated with basalt scoria. A second explanation is that much slipping occurred after the eruption, both on a small scale by rock fall and on a larger scale by large blocks slumping inwards. The latter were probably caused by the numerous cracks from which gases escaped after the eruption.

MAGNETIC ANOMALIES

In order to find the extent of the dike, magnetic (vertical force) measurements were made across the fissure using a Schmidt-type variometer and the magnetic anomalies associated with each traverse, together with those made by Watson-Munro (1938, map 2, and fig. 1), are shown in Fig. 1. As the basalt has a large total magnetisation, due mainly to its remanent (permanent) magnetisation (Table 1), and the rhyolite has a small total magnetisation, there is a large contrast between the two rock types at Tarawera.

TABLE 1—Magnetic Properties of Tarawera Rocks

	Basalt	Basalt Scoria	Rhyolite
Susceptibility (k) (c.g.s. units)	$1{,}400 \times 10^{-6}$	900×10^{-6}	300×10^{-6}
Induced magnetisation (c.g.s. units) (H = 0·6 oersteds)	840×10^{-6}	540×10^{-6}	180×10^{-6}
Remanent magnetism (c.g.s. units)	$30{,}000 \times 10^{-6}$	$17{,}000 \times 10^{-6}$	400×10^{-6}

Basalt outcropping at the bottom of the fissure can be correlated with a large sharp anomaly occurring in all magnetic profiles from B through to E (Fig. 1). The shape of the anomaly is typical of that produced by a narrow dike, rather than a massive body with aligned vents, which confirms the geological observations. Since the anomaly appears in profile E, and probably in profile F but not in profiles G or H, the dike must terminate somewhere beneath Lake Rotomahana. The absence of a large sharp anomaly in profile A indicates that the dike does not extend beyond the Complex in a north-easterly direction. The dike therefore has a length of less than 6 miles, and is limited to the Complex.

To determine the width of the dike from the magnetic anomalies it is necessary to know the depth of the top of the dike. Since none of the magnetic profiles cross the fissure where the dike is exposed, the depth of the dike below the surface scoria is not known, and no accurate width determination can be made.

Another sharp anomaly appears in profiles B, C, and D about 300 yd to the south-east of the main fissure, and is similar to that produced by the main dike, yet there are no surface features to account for it, except for two possible small explosion craters (max. diameter 50 ft) to the south of Ruawahia Trig No. 2. The conclusion drawn is that the second anomaly is caused by another dike parallel to the main fissure. The sharpness of the anomaly suggests the dike lies close to the surface, and since it is not shown in profiles A and E this dike must be confined to the rhyolite domes. This second dike was probably emplaced before, or during the early stages of the 1886 eruption, and was buried by basalt scoria ejected from the main fissure.

Smaller magnetic variations on the flanks of the main anomalies and in profiles A, G, and H can be attributed to variations in the thickness of basalt scoria overlying the rhyolite, and to topographic effects. The large negative values occurring in profile F are also probably due to topography.

ACKNOWLEDGMENTS

The writers thank the Geophysics Division, Department of Scientific and Industrial Research, Wellington, for the use of a Watts Magnetometer and for measurements of the magnetic properties of Tarawera rocks. Dr M. P. Hochstein and Mr R. R. Dibble of the Geophysics Division are thanked for constructive criticism of the draft.

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A SOURCE FOR VOLCANIC MATERIAL IN THE MOHAKATINO BEDS

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ABSTRACT

What is presumed to be the covered remnant of a large volcano has been revealed by magnetic studies off the Taranaki coast. Its situation is such that it is probably the source of the andesitic debris in the tuffaceous sediments of the Mohakatino Group.

INTRODUCTION

The Mohakatino Group, comprising sandstones and mudstones with varying amounts of tuffaceous material, occurs in northern Taranaki from Whangamomona as far north as Tirua Point near the remnant hornblende andesite volcano Whareorino. By far the most distinctive of the Mohakatino beds is an andesitic tuff which contains many "streaks and nests of hornblende, augite and feldspar crystals and fragments" (Henderson and Ongley, 1923, p. 43).

The beds "supposed to belong to the Mohakatino Series" to the south-east in the Ohura district have much less volcanic debris in them and "undoubtedly this region was far from the volcanic vents active during Mohakatino times" (loc. cit. p. 47). According to Henderson and Ongley (1923, p. 55) "it seems highly probable that this material was derived from Whareorino or a neighbouring volcanic vent. The amount and coarseness of the volcanic material in the tuff increase from south to north and from east to west, attaining a maximum on the coast a little north of the mouth of the Waioroko, a point 10 miles south of Whareorino".

Glennie (Arnold, 1959) came to the conclusion, "based on the distribution of the pyroclastic material in the Mohakatino Formation" that the volcano responsible for the supply of volcanic material in the Mohakatino was out in the Tasman Sea.

Fleming (1962, p. 79), in a figure showing his interpretation of upper Miocene geography (Waiauan–Tongaporutuan) locates "Mohakatino volcanoes, active Sc–Tt" off the coast of northern Taranaki. A recent total magnetic force survey by seaborne proton precession magnetometer has confirmed Glennie's and Fleming's inference of volcanoes off the coast of the Mokau region and discovered the probable source of the Mohakatino tuffs.

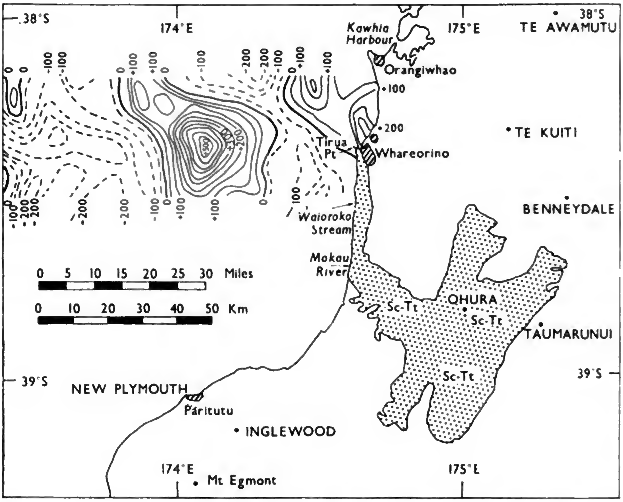

FIG. 1—Magnetic anomalies (in gammas) off the coast of western Taranaki. These anomalies were derived from total magnetic force measurements and a regional gradient after Burrows (1967) has been removed. The Mohakatino beds are stippled and the hornblende andesite volcanoes of western Taranaki are cross-hatched.

MAGNETIC ANOMALIES

Figure 1 shows the distribution of the Mohakatino Group according to Hay (1967) and Kear (1960). The mouth of the Waioroko Stream, just south of the region of maximum coarseness of the andesitic debris, is indicated. The results of the total magnetic force survey along east–west lines at 5 mile intervals, reduced to a residual anomaly map by the removal of a regional field based on Burrows (1967), are also shown in the figure. There are two principal anomalies. The eastern one which leaves Tirua Point and runs close to the coast is associated with the western flank of the New Zealand Marginal Syncline throughout virtually its entire length (Hatherton, 1966, 1967). The western anomaly, whose circular form suggests a volcanic origin, is about 550 gammas in amplitude, 30 km in diameter and is centred about 45 km from the coast. The nearest part of the coast is that between Tirua Point and the mouth of the Waioroko Stream, the region of maximum coarseness of the andesitic debris in the Mohakatino tuffs. There is probably little doubt that this magnetic anomaly is due to a remnant andesitic volcano, the source of the Mohakatino volcanic debris, and that this volcano was active in upper Miocene time.

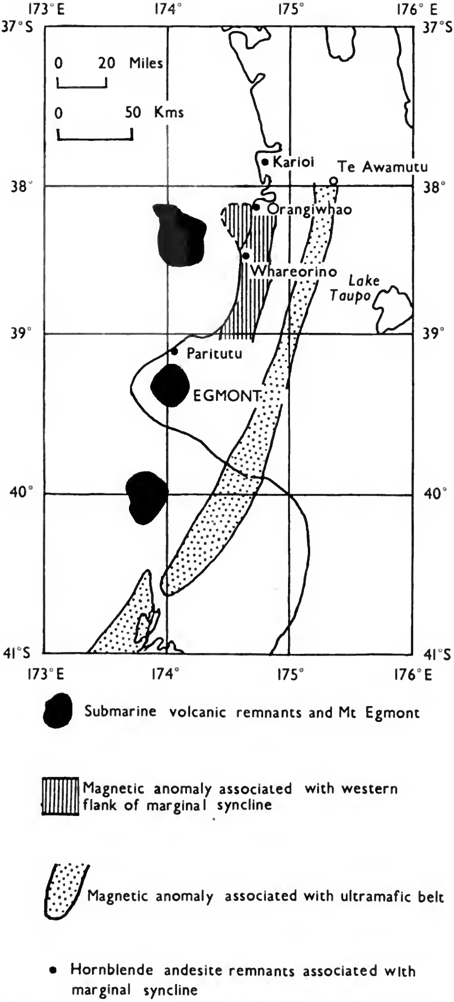
173°E
174°
175°
176° E
37°S
37°S
0 20 Miles
0 50 Kms
Karioi
Te Awamutu
38°
38°
Orangiwhao
Whareorino
Lake Taupo
39°
39°
Paritutu
EGMONT
40°
40°
41°S
41°S
173°E
174°
175°
176°E
Submarine volcanic remnants and Mt Egmont
Magnetic anomaly associated with western flank of marginal syncline
Magnetic anomaly associated with ultramafic belt
Hornblende andesite remnants associated with marginal syncline

FIG. 2—Distribution of known and inferred volcanoes of western Taranaki and offshore Taranaki and position of ultramafic belt inferred from geophysical measurements.

Another magnetic anomaly of similar size and slightly smaller amplitude (~300–400 gammas) has been mapped to the south of Mt Egmont (Hatherton, 1967). Again there is nothing in the bathymetry to denote the existence of a volcano, and an upper Miocene age for this volcano too would be appropriate. The distribution of volcanoes in western and offshore Taranaki is given in Fig. 2 which shows several lineations. The position of Mt Egmont is the ambiguous feature on this map. It can be classed as one of the western Taranaki volcanoes, together with Karioi, Orangiwhao, Whareorino, and Paritutu, which lie on an arc parallel to the eastern boundary of the marginal syncline as expressed by the magnetic anomaly of the ultramafic belt. Or it can lie on an arc of similar curvature which includes the two offshore volcanoes and which is slightly divergent from the marginal syncline. Studies of the chemistry and ages of the western Taranaki volcanoes, including Mt Egmont (Hatherton, in press), have not yet resolved this ambiguity.

I shall be discussing the geophysical significance of these volcanoes and of all other andesites in the North Island at greater length in a forthcoming paper.

ACKNOWLEDGMENT

The measurements were made during a New Zealand Oceanographic Institute cruise on m.v. *Taranui.* Mr R. B. Williams operated the magnetometer.

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PALYNOLOGICAL TECHNIQUES USED IN NEW ZEALAND

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ABSTRACT

Methods are described for extracting organic-walled plant microfossils from New Zealand sediments. Modifications to existing techniques and laboratory equipment are featured. Emphasis is given to safety and protection of equipment. Methods for recording preparation details, mounting small residues, and storing unmounted residues are described.

INTRODUCTION

Cranwell and Harris performed the first palynological extractions in New Zealand in 1937 using the alkali and acetylation method on peat and lignite (Dr W. F. Harris, pers. comm.).

Te Punga (1945) published the first description of a microfossil extraction technique (from coal) in New Zealand, and added to it in two later papers (Te Punga, 1948, 1949).

Couper (1951a) mentioned the beginning of palynological research in New Zealand. In 1951b he described his method of macerating lignite. An outline of demineralisation and maceration of oil shale and mudstone was given by Couper (1952). Moar (1958a, b, 1959) gave brief details of pollen and spore extractions, mainly from peat. Harris (1961) reported difficulty in concentrating microfossils from Little Barrier Island peat samples. Shaw (1961) briefly mentioned microfossil extractions from coal performed at the New Zealand Geological Survey. McIntyre (1962) used the silica depressant method (Arms, 1960) for concentrating the low ratio microfossil content from carbonised samples. Norris (1962) outlined the extraction method applied to Couper's holotypes and emphasised the type of mounts and their preservation. McIntyre (1963) noted the effect and variability of different chemical treatments on the size of pollen grains. McIntyre and Wilson (1966) recorded in brief the method used to macerate Antarctic sediments. Wilson (1967) noted the ease with which microfossils were recovered from Campbell Island sediments.

A more detailed account was given by Couper (1953) who considered the effect of oxidation, alkali, and acetylation methods on the microfossil content of samples. A detailed study was made by Harris (1956) who investigated

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the influence of natural agents, laboratory reagents, and conditions of preservation on pollen morphology. He distinguished between swelling and over expansion of pollen. Differences in size according to the preparation method used were noted. The effect of ultrasonic irradiation on modern pollen and spores was investigated by McIntyre and Norris (1964). They considered that their results could be used for comparison with work on fossil pollen and spores.

Traverse (1956) and Brown (1960) compared Couper's methods with other published techniques.

Subtle variations of existing techniques often make them easier to apply, less time-consuming and produce better yields of microfossils from New Zealand sediments. Whether samples yield microfossils at all may depend on how they are handled in the laboratory during extraction. Some techniques are destructive to New Zealand microfossils. Three authors in particular have drawn attention to sequences in extraction methods which are liable to destroy the microfossil content of samples (Faegri and Iversen, 1964; Hafsten, 1959; Wilson, 1964).

MECHANICAL TREATMENT

Non-cemented samples are treated in a rotary sample washer similar to that described by Felix (1963). Samples are placed in dilute non-ionic detergent and rotated at 40 r.p.m. for 24 hr, after which they are transferred to centrifuge tubes for washing, flotation, and acetylation. This rapid method is used on as many samples as possible.

Before chemical treatment, all hard and cemented samples containing an appreciable amount of mineral material (i.e., other than coal and peat) are crushed to less than 500 μ with a mechanical pestle and mortar. This can be readily cleaned with an abrasive cloth. Sample weight varies from 10 to 20 g depending on density, grade, and carbonaceous content.

Crushing samples reasonably fine greatly aids demineralisation; however, it has been noted that microfossils may be damaged by mechanical treatment in the laboratory (Gray, 1965b). In the author's experience the only microfossils affected by crushing samples to 500 μ are the large, fragile microplankton. For these, the samples are lightly crushed and selectively sieved to give the 1–2 mm fraction for processing.

DEMINERALISATION

Carbonates

Samples containing carbonates are treated with an excess of 10% hydrochloric acid until effervescence ceases. A little concentrated acid is then added to check that all carbonates have been eliminated.

Silicates

Dry samples are first saturated with 95% ethanol in 250 ml copper beakers. All beakers are suspended in cool tap water (*ca.* 14°C) before 75 ml of 68% hydrofluoric acid are added to each sample. The acid is added gradually while stirring. The beakers are then placed on an oscillating hotplate (oscillating, but cold) to keep the samples suspended in the acid. When vigorous reactions have ceased, the hotplate is switched on to operate at 110–120°C and samples are digested until about 35 ml remain (60–70 minutes). After cooling, the spent acid is removed by centrifuging, in capped 50 ml polypropylene tubes, and decanting.

Hydrofluoric acid attacks silicates with an initially vigorous and dangerous exothermic reaction. The addition of ethanol to dry samples subdues this reaction but, since ethanol is volatile, it soon evaporates and does not appreciably dilute the acid. Suspending the beakers in cool water dissipates the excess heat generated when the acid is first added.

Residues are next treated by filling the tubes with boiling concentrated hydrochloric acid which is stirred in with a polypropylene stirring rod. The tubes are heated in a bath filled with Lissapol detergent, for 10 min. at 120°C. (The temperature of the acid in the tubes does not, however, exceed 95°C.) They are then lifted out of the bath, are rinsed in hot water to remove the film of detergent, are centrifuged and the acid decanted.

This process is repeated with 10% hydrochloric acid at least twice—until the decant loses its yellow colour. After washing with distilled water, an inspection mount is made.

If the residue is in a gel, i.e., adheres to the stirring rod, it can usually be dispersed (see Ultrasonic Treatment). If much free mineral material remains the sample may benefit from immediate flotation, but most samples contain little mineral material and can be oxidised immediately.

OXIDATION

The author is acutely aware that microfossils have different oxidation susceptibility (Havinga, 1964) and that strong alkali treatment can be harmful. Therefore oxidation and neutralisation are done with the utmost care.

Oxidation is by Schulze treatment (Schulze, 1855; Manum, 1956), i.e., by adding 50–100 mg of potassium chlorate and 10 ml of concentrated nitric acid to the residues in polypropylene tubes. Both reagents should be increased for samples containing a large amount of organic material. The acid is diluted in the tube when a satisfactory reaction has occurred or after 10 min if there is no apparent reaction. After centrifuging, the residues are neutralised with 5% ammonium hydroxide, centrifuged again and washed. A second inspection water mount is then made.

ACETYLATION

The samples are pre-washed with 15 ml of glacial acetic acid, then treated with 20 ml of acetylation reagent per tube. The residues in the tubes are stirred and warmed in a water bath at 90°C for 10 min. After centrifuging the residues are washed in acetone.

Acetylation of residues (Erdtman, 1934, 1943; Gray, 1965b) removes unwanted cellulose material. It also improves the microfossils for microscopy by increasing the contrast of their external morphological details. Extreme care is taken to avoid over treating residues since this causes swelling of microfossils (Couper, 1953; Harris, 1956; McIntyre, 1963).

SHORT CENTRIFUGING

Short centrifuging (Funkhouser and Evitt, 1959) is the final treatment given to all samples. After washing, the residues are transferred to 15 ml conical glass tubes and short centrifuged by stirring, immediately centrifuging and decanting (see Centrifuging). The process is repeated until the supernatant liquid is clear—four times is usually sufficient. A permanent mount is then made.

SPECIAL TREATMENTS

Any of the following additional treatments may be required:

(*a*) Should an excess of dark brown to black organic material remain, it is treated with chromium trioxide and nitric acid (Funkhouser and Evitt, 1959), neutralised with 5% ammonium hydroxide, washed, and stained.

(*b*) An excess of light brown organic material can be overcome by treating with 2% sodium hypochlorite, neutralisation with 5% ammonium hydroxide, wash, and stain (Hoffmeister, 1960).

(*c*) Persistent mineral material can be readily removed by density separation (see Flotation).

FLOTATION

Residues in 15 ml conical glass tubes are acidified by washing in 10% hydrochloric acid after which 10 ml of zinc bromide solution (Sp. Gr. 2·0) is added (Staplin *et al.*, 1960). The mixture is stirred thoroughly, and if flocculation occurs this is overcome by brief ultrasonic irradiation. After centrifuging the tubes are given a quick swirl before decanting the float fraction into 50 ml glass tubes. Both sets of residues are washed with 10% hydrochloric acid. The float fractions are then transferred to 15 ml tubes.

This method is at least as effective as other methods of heavy liquid flotation (Funkhouser and Evitt, 1959; Staplin *et al.*, 1960), is simpler, and uses less zinc bromide solution.

COAL MACERATION

Samples of approximately 5 g are crushed to less than 300 μ and macerated by Schulze reagent, i.e., half their volume of dry potassium chlorate and 15 ml of concentrated nitric acid are added to the sample in 50 ml polypropylene tubes. This is diluted when sufficient oxidaton has occurred, or at the end of 15 min if there is no apparent reaction. After centrifuging and decanting, the residues are neutralised with 5% ammonium hydroxide. All coal samples undergo acetylation, after which a mount is made.

If maceration is incomplete, appropriate Special Treatment (see above) is given. Sodium hypochlorite treatment before treating with Schulze reagent gives very workable yields from some coals (Lee, 1964). When fusain is present it can appear as fine particles throughout the final preparation and because of its inert nature cannot be eliminated chemically. It can, however, be removed by ultrasonic irradiation.

PEAT EXTRACTIONS

A modification of Churchill's method has been adopted (Churchill, 1957). Gauze tubes 4 × 1·25 cm of 177 μ aperture (80 mesh) are filled with peat. Care is taken not to compress the peat, which will clog the gauze. They are stoppered and suspended in 50 ml polypropylene tubes containing 5% potassium hydroxide and heated for 10 min in the heating bath.

A good method of suspending the gauze tubes in the 50 ml tubes is to heat the end of an 8 cm length of wire in a bunsen burner flame and immediately force it into a suitable rubber bung. When the wire is bent at right angles in the middle and the gauze tube attached, the wire will hang on the lip of the 50 ml tube. The wire can also be used as a handle to agitate the gauze tube.

Microfossils are concentrated in the alkali as convection and some manual agitation causes fine particles to filter into solution while coarse material is retained by the gauze tube. After heating, the alkali solution is centrifuged, washed, and the residue inspected as a water mount. It may be stained or further treated by acetylation before mounting permanently. Some peat contains mineral material which can readily be eliminated by flotation.

ULTRASONIC TREATMENT

It has been noted by several authors that ultrasonic treatment can be destructive to organic-walled microfossils. These effects appear to be at a minimum before oxidation has taken place (McIntyre and Norris, 1964) and ultrasonic irradiation is used to great advantage on many samples at that stage with negligible effect on the microfossils. It should be noted that several factors influence the intensity of cavitation with individual machines (Weissler, 1953; Weissler and Hine, 1962). Details of the machine used are given below (see Equipment).

To treat the samples they are transferred to 50 ml glass tubes (glass appears to transmit ultrasonic energy more efficiently than polypropylene) with 15 ml of dilute non-ionic detergent to aid dispersion. Samples are irradiated for 10 min after which the tubes are immediately removed, filled with water, and the residues stirred, centrifuged, and decanted. Washing is repeated, if necessary, until the supernatant liquid is clear.

Ultrasonic irradiation is occasionally used briefly after oxidation to deflocculate residues (Funkhouser and Evitt, 1959; Stevens *et al.,* 1960), but is only used for more than a minute when dispersing fusain (see Coal Maceration). Here the benefits of eliminating fusain must be equated against possible breakage of microfossils.

The ultrasonic vibrator frequently enables equipment to be cleaned which would otherwise have to be discarded. This is particularly so with 15 ml conical glass tubes and gauze tubes used for peat samples.

CENTRIFUGING

Although methods of centrifuging are largely determined by the particular machine used, the following points may be noted about the author's centrifuging practices:

(*a*) Standard centrifuging for 50 ml tubes is four minutes at 2,000 r.p.m., after which it can be braked to stop if required. R.C.F. at the tip for this centrifuge is given as 1,800 at 2,900 r.p.m.

(*b*) When centrifuging viscous liquids, e.g., zinc bromide solution, 5 min at 2,000 r.p.m. is sufficient, but without braking as this causes resuspension.

(*c*) Following ultrasonic irradiation 50 ml tubes are centrifuged for only 15 sec at 2,000 r.p.m. and coasted to a stop.

(*d*) 15 ml conical glass tubes required only 2 min at 2,000 r.p.m. R.C.F. at the tip for this centrifuge is given as 1,000 at 2,000 r.p.m.

(*e*) Short centrifuging of freshly stirred residues is effected by accelerating them in the centrifuge to 2,000 r.p.m. in about 30 sec, at which point it is switched off and coasted to a stop. The tubes are removed and the contents decanted immediately.

SLIDE MOUNTING

Disposable semi-micro pipettes are invaluable for transferring small residues from tube to slide. They can also be used to blow air through larger, aqueous residues to give homogeneous solutions from which representative samples can be drawn off for mounting. Pre-cleaned slides and cover glasses are used. Mounts are made in glycerine jelly, which is readily made and is a convenient water-miscible mountant. The author uses wood toothpicks which are wide and flat at one end, for spreading and mixing the residue with the mountant.

It has been noted (Andersen, 1960) that glycerine jelly has two undesirable properties, namely: (*a*) that its refractive index is not entirely suitable, and (*b*) it is not considered to be permanent. The author has not found a mountant as convenient to use with superior optical properties to glycerine jelly. Permanence is relative—if the mounts are adequately sealed and stored horizontally they are quite permanent (Norris, 1962).

Cover glasses are sealed with clear lacquer which remains pliable and can be readily removed without disturbing the mount. Slides are ready for use in a few minutes.

STORAGE OF SAMPLES

Some of the original material is kept in 500-gauge polyethylene bags, usually 15 × 10 cm, but larger samples from important localities, e.g., type sections, in bags 30·5 × 20 cm. Samples are labelled by writing on the bags with a felt-tipped marker pen.

To store processed residues, a few drops of 5% phenol solution are added to each tube and the aqueous residues are transferred to labelled, 10 ml, glass vials with plastic caps. The top 3 mm of the vials are filled with 10 centistokes silicone fluid from a dispensing bottle. Phenol prevents fungal growth and the inert silicone fluid floats on the water to prevent desiccation. This is considered a more practical method than dry storage of residues (Dempsey and Urban, 1965) because residues are fully processed before storage and tedious desiccation is not required. By decanting the excess fluid from residues in the vials they are immediately available for further processing, additional slides, or for single mounting.

Slides are stored horizontally in steel slide cabinets.

EQUIPMENT

A comprehensive list of equipment has already been given by Gray (1965a). The following further brief notes on equipment are offered:

(*a*) 250 ml beakers containing samples in hydrofluoric acid are digested on a thermostatically controlled oscillating hotplate (45 × 34 cm) (Staplin *et al.*, 1960). This is a safe and efficient method.

(*b*) Centrifuges in palynological laboratories must be versatile and ruggedly constructed. The machine used at the N.Z. Geological Survey (supplied by International Equipment Company, Boston 35, Mass., U.S.A.) loads 8 × 100 ml, 16 × 50 ml, or 32 × 15 ml tubes on one eight-place combination head.

(*c*) The electric heating bath contains concentrated detergent (Lissapol, an I.C.I. product) and operates at 120°c. It requires no attention, causes no steam problem, and does not corrode equipment.

(*d*) The ultrasonic vibrator is a Narda Sonblaster series 600 generator and operates a 40 kc/sec and 60 W average output, coupled to a tank activated by a barium titanate transducer. This equipment permits good control of irradiation given to residues.

(*e*) The author uses a tube mixer for stirring residues whenever possible because of its efficiency. This avoids breakage of fragile specimens and minimises possible contamination.

(*f*) A slide mounting hotplate with thermostat control and chromium plated top is used and gives good visibility during slide mounting. It keeps the mountant ready for immediate use.

SAFETY AND PROTECTION

A face guard and two-dip, half gauntlet rubber gloves are worn in addition to a laboratory coat when using chemicals in the course of sample processing.

The centrifuge is placed in line with the fume cupboard, so that the operator at the fume cupboard need only turn through 180° to use it.

Corrosion of the centrifuge has been a problem—inevitably some fumes escape from capped tubes and not all tubes can be fitted with caps. Coating all parts in the bowl with a layer of silicone grease gives a fair measure of protection, but its application is time consuming and corrosion is not restricted to the bowl and contents.

A modified vacuum cleaner is now used as a blower inserted in the lid (see Fig. 1) and a 5 cm exhaust duct leads from the bottom of the bowl to the fume cupboard. To clear fumes, the blower is switched on briefly just before the centrifuge stops. This modification, while not altering the centrifuge structurally, protects the centrifuge and prevents the operator inhaling fumes being drawn past him toward the fume cupboard.

Equipment used in the fume cupboard requires protection from corrosion. "Chloroseal", a paint described as a chlorinated rubber compound with acid resistant properties, has been used successfully. Spray-on lacquer and plastics such as "P.T.F.E." have possibilities, but have not been proved. It is desirable to give a suitable protective coating to new equipment.

Hazards

(*a*) Care must be taken not to allow water to enter the hot (120°c) detergent-filled bath.

(*b*) Ultrasonic vibrators can be noisy and injurious to personnel if they operate at frequencies near the human audible range. The machine used at the N.Z. Geological Survey is safe since it operates at a fixed frequency of twice the human audible range.

RECORDS

Preparation sheets are used in the laboratory to record full details of treatments given to each sample. Since samples are usually prepared in multiples of eight, cyclostyled sheets with eight horizontal columns, 22 mm wide and divided into 12 vertical columns 26 mm wide, are used. The first two columns on the left are used for sample numbers, the remaining ten are subdivided horizontally into three to record (i) reagent used, (ii) details of any visible reaction, and (iii) microscopic observations. Using both sides of the sheet, details of twenty treatments of each sample can be recorded.

Advantages

(*a*) In return for a little time spent recording details as the preparation proceeds, a permanent record of individual sample treatments is compiled.

(*b*) If desired the recorded procedure can be repeated or applied to any other sample, i.e., of the same lithology.

(*c*) Full details of important reactions, e.g., oxidation, are available.

(*d*) An improved procedure for any given sample can be planned by referring to this record.

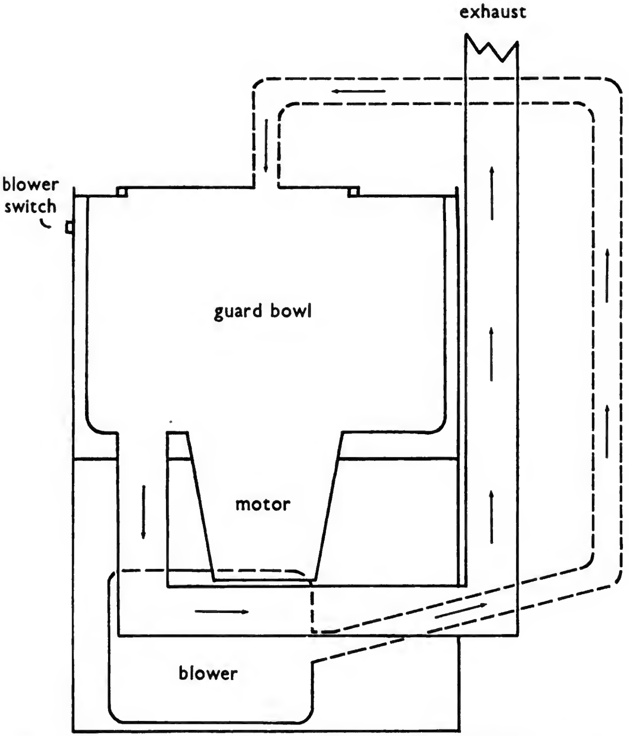

FIG. 1—Simplified cross section of centrifuge with accessory blower and exhaust system.

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EXPERIMENTAL DEFORMATION OF ARGILLITE: PRODUCTION OF KINK FOLDS AT 450°C AND 1 KILOBAR P_{H_2O}

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ABSTRACT

Kink folds have been produced in argillite specimens deformed at varied strain rates under simulated metamorphic conditions of 450°C and $P_{H_2O} = 1$ kilobar. Folds were formed at 13% shortening. The only mechanism of deformation recognised was mechanical re-orientation of mineral grains.

INTRODUCTION

Paterson and Weiss (1962, 1966) produced kink bands and conjugate folds by deforming dry specimens of phyllite and mica schist. Their experiments were at room temperature and 5 kilobar-confining pressure (radial expansion permitted) with high rates of strain (5%–10% per minute) and total strains of 5% to 80%. Herein is described the deformation of brass-jacketed specimens of an argillite resulting in kink folds (Turner and Weiss, 1963, p. 114; Dewey, 1965, p. 460). Each experiment was of several days duration at 450°C with 1 kilobar water vapour pressure. Radial expansion was constrained, the rate of strain slow and total strains varied from 13% to 46%. The confining pressures are not known.

An argillite from the Manuherikia River (Mutch, 1963, grid ref. S33/6191) of the prehnite-pumpellyite metagreywacke facies was chosen for these experiments at 450°C and 1 kilobar water pressure. Considerations bearing on this choice were: (*a*) It is fine grained (estimated 15 micron average grain size) and therefore likely to react or recrystallise more easily than the coarser sandstones under the above P-T conditions. (*b*) It is thought to be part of the parent material for the neighbouring schists (Grady, 1968). (*c*) Slaty cleavage is well developed. (*d*) There are no fractures or kink folds.

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Detrital minerals in the argillite include quartz, feldspar, epidote, and minor opaques. Some quartz shows strain features but most is strain-free. Feldspar is completely albitised and epidote is sometimes partly rimmed by pumpellyite. Detrital or reconstituted groundmass quartz and albite make up about 50% of this rock, while epidote is minor (5%). Secondary muscovite and chlorite also form prominent components (*c.* 35%), and together, by their preferred orientation, defined the slaty cleavage. Pumpellyite is minor (5%–10%) and of pale colour (iron-poor). Opaques are partly iron oxides and partly very fine graphitic material.

METHOD

Preliminary hydrothermal experiments with powdered (minus 350 mesh) argillite in both sealed and unsealed tubes at 450°c and $P_{H_2O} = 1$ kilobar showed that in the 1 to 7 days no significant mineralogical changes were detectable by X-ray and optical methods.

Cylinders of argillite were cored with a diamond bit, parallel to slaty cleavage. Specimens were trimmed to suitable lengths and fitted with thin brass jackets after careful measurement of diameter and length.

Means and Rogers (1964) have described the experimental equipment and procedures.

The furnace temperature was controlled at 450°c by a Pt–Pt Rh (13%) thermocouple and a Transitrol temperature controller, and the water pressure was maintained at 1 kilobar with a Sprague pump. The stress applied to the piston head was measured with a strain gauge. Friction on the piston was negligible and was disregarded in calculating the stress applied to the specimen. The dimensions of the brass jackets and steel cylinder are shown under Fig. 1.

Fabrics of the argillite and of the experimentally deformed specimens were examined in thin section and by comparison of the X-ray diffractometer peak heights obtained from the three oriented slabs of undeformed argillite with those obtained from polished faces of the deformed specimen cut parallel and perpendicular to the piston face. The principal peaks examined were the basal reflections of chlorite and muscovite. As the changes in the fabric of the specimens produced during the experiments were only local the X-ray diffractograms did not detect them.

RESULTS

The deformation was of two types, determined by the position of the anvil as shown in Fig. 1. In experiments 1(a) and 2(a) there was shortening with little or no radial expansion, while in 3(b) there was shortening with extrusion over the apex of the truncated cone. Details of the deformations are shown in Table 1.

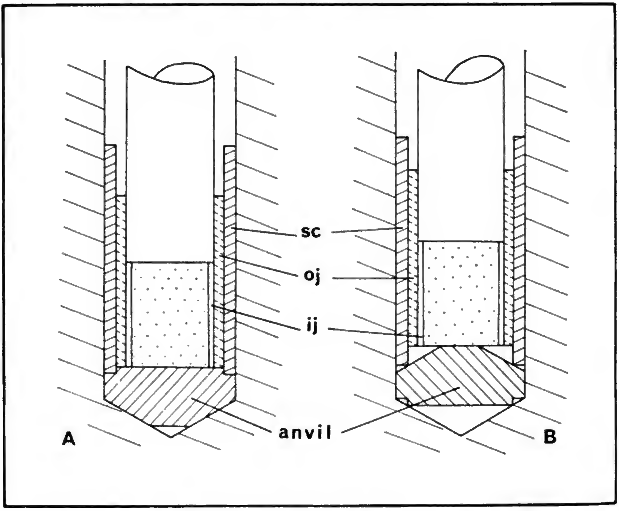

FIG. 1—Arrangement of piston, specimen, brass jackets (ij and oj) and steel cylinder (sc) for (A) shortening with little or no radial expansion, (B) shortening with extrusion over the apex of the truncated cone. (Not to scale.) ij = 11·1 and 11·3 mm internal and 12·4 mm external diameter 12·3–15·8 mm long. oj = 12·5 i.d. 16 mm e.d. 20 mm long. sc = 16 mm i.d. top and 17 mm i.d. bottom. 21 mm e.d. 28.5 mm long.

TABLE 1—Details of Deformation

Experiment	Drive	Hours	Strain Rate (%/hour)	Total Strain (%)	P_{H_2O} (kilobar)
	Manual	·93	10	9·3	0
1(a)	Manual	0·5	12	6·0	0
	Mechanical	69·0	0·025	1·7	1
	4 Kb static load	96·0	Nil	0	1
		166·43		17·0	
	Mechanical	50	0·004	0·2	1
2(a)	Manual	0·33	40	13·3	1
	Static load 5 → 4 Kb	16	Nil	0	1
		66·33		13·5	
	Interrupted	109	0·027	30	1
	Mechanical	67	Nil	......	1
3(b)	Manual	2·5	6·42	16	1
		178·5		46	

From experiments 1(a) and 2(a) the general observations were:

(*a*) Occasional sharp sounds, associated with decrease in stress value and increase in strain. (On one occasion a decrease of 0·77 kilobars in stress, and an increase of 0·5% total strain, were measured.) Possibly these are associated with the sudden movements forming kink folds.

(*b*) There were no mineralogical changes.

A thin section cut 1 mm from bottom and perpendicular to the axis of a cylinder shortened 17% showed no changes. Means and Rogers (1964) found that the fabric and mineralogy of end sections of deformed cylinders were not necessarily representative of the fabric in the body of the cylinder. Thus a section cut parallel to the axis showed kink bands in the slaty cleavage as lens-like zones up to 2 mm long and 0·5 mm wide. There were two sets of such zones developed at about 45° to each other and symmetrically arranged about the trace of the slaty cleavage. One set was much better developed than the other. Individual kink zones were well separated and the two sets did not intersect to a marked degree. In fact, at about the inferred point of intersection, the intensity of folding died out. The sense of movement associated with the formation of the kink zones is shown in Fig. 2.

Part of the observed strain was the result of rupture and relative movement of blocks within the specimen. Unfractured blocks up to 8 mm × 6 mm are present. These correlate with areas of undeformed slaty cleavage. Fracture surfaces are at no regular angle to the cylinder axis. A concentration of fractures is seen in zones running from the top and bottom edges of the specimen and passing diagonally through its centre, suggesting a cone of fracture surfaces.

A thin section cut parallel to the axis of a cylinder shortened 13·5% showed a narrow irregular zone of re-orientated slaty cleavage (Fig. 3) in which the fabric has been rotated up to 90°. There is little evidence of deformation in the rest of the specimen. Displacements on fractures and associated movement again accounted for part of the total strain. Undeformed blocks correlate with areas of undeformed slaty cleavage in Fig. 3. Fracture surfaces tend to run diagonally through the specimen.

This specimen showed more extensive development of fractures than the one shortened 17%. However, it was strained more rapidly and remained under load, without deformation for a shorter time, 16 hr compared with 96 hr. Possibly opportunity for healing recrystallisation is optimum when there is no, or only slow deformation. Alternatively the fracturing is a result of the greater pore pressure of water present initially (*see* Griggs, 1936, pp. 566–567; Heard, 1960, pp. 216–223, 225–226).

The significant result in these two experiments is the production of re-oriented fabrics under simulated metamorphic conditions, without extensive fracturing.

Observations from experiment 3(b) were:

(*a*) There were no mineralogical changes.

(*b*) A thin section cut parallel to the cylinder axis showed that deformation was concentrated near the base of the specimen and that the argillite was extruded around the truncated cone of the anvil (Fig. 4). Kink zones

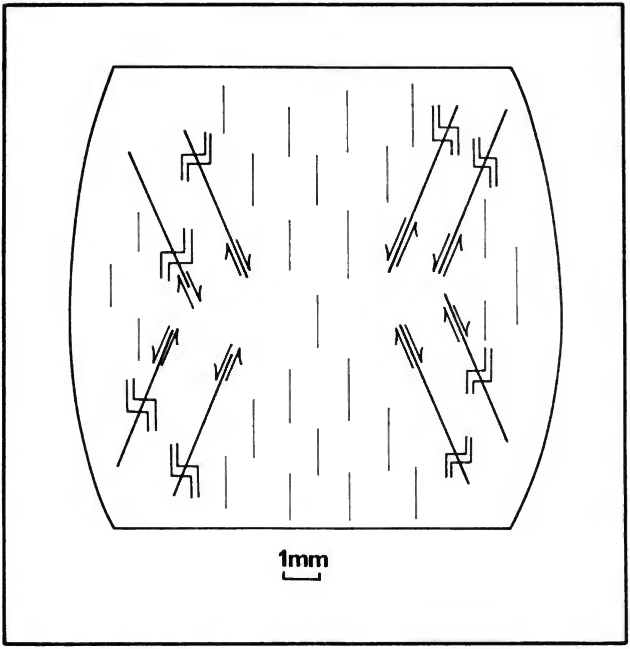

FIG. 2—Diagrammatic sketch of section parallel to cylinder axis from specimen shortened 17% showing directions of movement along kink zones.

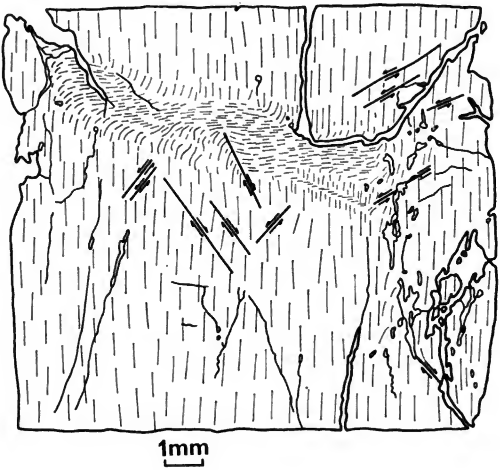

FIG. 3—Sketch of thin section cut parallel to cylinder axis from specimen shortened 13·5% showing narrow irregular zone of re-oriented slaty cleavage. Small arrows show directions of movement on small kink zones.

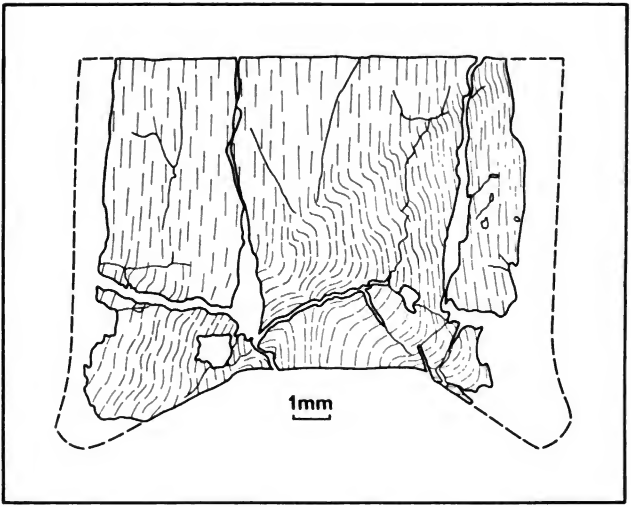

FIG. 4—Sketch of thin section cut parallel to cylinder axis from specimen shortened 46% showing kink zones associated with extrusion.

are associated with the extrusion movements and one major sinuous kink zone extended high into the specimen. Slaty cleavage planes are remarkably continuous throughout the specimen and there was notable cohesion within the fabric, in which re-orientation involving 90° block rotation of mineral grains was evident. The development of fractures and the associated movements accounted for part of the strain. Fractures are concentrated in the central part of the specimen where deformation was greatest (Fig. 4) and are surrounded by blocks of undeformed, unfractured argillite.

CONCLUSIONS

Preliminary hydrothermal experiments on powdered argillite showed no mineralogical changes at 450°C and 1 kilobar P_{H_2O}. There was no evidence in thin section that deformation had facilitated reaction. Optical studies of the deformed specimens revealed no change in the grain size of constituent minerals. These observations lead to the conclusion that recrystallisation is not a major mechanism of the re-orientation achieved in these experiments. Therefore, in both types of experiments, it is concluded that the mechanisms of re-orientation are mechanical.

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POTASSIUM-ARGON MINERAL DATES ON INTRUSIVE ROCKS FROM THE FOVEAUX STRAIT AREA

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ABSTRACT

Potassium-argon dates on biotite and hornblende separated from six intrusive rocks from the north shore of Foveaux Strait (between Pahia Peninsula and Bluff) and Ruapuke Island range from 253 m.y. (late Permian) to 133 m.y. (early Cretaceous). The younger dates, however, are discarded because of wide discordance between the biotite and hornblende determinations, and petrographic evidence of alteration. The accepted range of ages is from 250 m.y. to 217 m.y., although the younger of these, corresponding to about middle Triassic, are regarded with caution because of minor discordance between the biotite and hornblende dates in the two rocks concerned. Nevertheless, the possibility that intrusion of some of the rocks extended into the Triassic is recorded and briefly discussed.

INTRODUCTION

Rocks for this reconnaissance study were collected (by I. Devereux and W. A. Watters) from the north shore of Foveaux Strait and Ruapuke Island. Mineral separations were largely carried out at the New Zealand Geological Survey, Lower Hutt, and the samples processed (by I. Devereux and I. McDougall) in the geochronology laboratory of the Department of Geophysics and Geochemistry, Australian National University, Canberra. The results are given in Table 1.

The procedures employed in determining the K–Ar dates have been described previously (McDougall, 1966; Cooper, 1963). Potassium is measured using the flame photometric method with lithium internal standard; duplicate determinations (Table 1) agree to better than 0·5%. Argon is determined by the isotope dilution technique; the isotopic analysis of the purified argon is made on a Reynolds-type mass spectrometer. Replicate measurements of the radiogenic argon content in this laboratory normally

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agree to within 2% as indicated by the results on biotite reported in Table 1. However, duplicate measurements on two hornblendes differ by about 5·% (Table 1), and this may be because of minor contamination of the mineral concentrates by biotite, rendering it difficult to obtain representative splits for argon analysis. The overall precision of measurement of a K–Ar date in the present paper is about ±5% at the 95% confidence level.

SAMPLES

KA3* (GA923*) (P32751*). Coarse grained hornblende-rich gabbro. Coast about 1 mile east of Barracouta Point, Bluff Peninsula (S181/282836†).

KA5 (GA925 (P32753). Coarse grained hornblende-rich gabbro. Coast about $\frac{1}{3}$ mile south-south-east of Pahia Point (S175/791093).

KA7 (GA927) (P32755). Slightly gneissic biotite tonalite. 1 mile south-east of Pahia Point (S175/798087).

KA9 (GA929) (P32757). Fine grained adamellite. Near mouth of Ouki Creek, 3 miles south-east of Pahia Point (S175/832073).

KA10 (GA930) (P32758). Tonalite with numerous amphibolite inclusions. West end of Kawakaputa Bay (S176/892029).

KA12 (GA932) (P32760). Tonalite. Near southern point of Ruapuke Island, eastern approaches of Foveaux Strait.

DISCUSSION OF RESULTS

Bluff

The intrusive rocks, mainly norite, at Bluff have been described in detail by Service who considered them to be late Paleozoic or at least older than middle Triassic (Service, 1937, pp. 187, 214). The date for KA3 hornblende (247 ± 10 m.y.) corresponds closely with the Rb–Sr date on biotite of the pegmatite from the Bluff norite reported by Aronson (1965) at 246 ± 7 m.y. The hornblende gabbro dated is similar to the coarse-grained hornblende rock mentioned by Service (1937, p. 208) as a phase of the main Bluff norite which is itself intimately intruded by the pegmatite dated by Aronson (1965).

Pahia Area

No detailed petrological work on the intrusive rocks from this area has been published. Wood (1966) includes them within the late Paleozoic Longwood Intrusives which comprise part of the Longwood Complex of Mutch (1957). In the eastern part of the Longwood Range the

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*Numbers prefixed by KA are for the field number given during collection. Those prefixed by GA are the reference numbers of the Department of Geophysics and Geochemistry, Australian National University, Canberra. The numbers prefixed by P are the catalogue numbers of samples held in the Petrology Section collection, New Zealand Geological Survey.

†Grid reference based on the sheet district of the 1 : 63,360 topographical map series (NZMS 1) and the national thousand-yard grid shown on this series.

TABLE 1—Potassium-argon Mineral Dates on Rocks from the Foveaux Strait Region, South Island, New Zealand

Sample No.	Mineral	K%	$^{*}Ar^{40}/K^{40} \times 10^{-2}$	% Atm. Ar^{40}	Calculated Age (m.y.)
KA3	Hornblende	0·112 0·113 } 0·112	(1) 1·510 (2) 1·579	55·3 73·0	242 253
KA5	Hornblende	0·260 0·261 } 0·260	(1) 0·992 (2) 0·946	41·0 35·5	163 155
KA7	Biotite	7·08 7·10 } 7·09	(1) 0·807 (2) 0·815 (3) 0·822	14·4 19·9 3·2	133 135 136
	Hornblende	0·609 0·618 } 0·613	0·991	8·2	162
KA9	Biotite	7·52 7·53 } 7·52	1·156	14·9	188
KA10	Biotite	7·42 7·39 } 7·40	1·289	7·7	209
	Hornblende	0·597 0·600 } 0·598	1·354	5·8	217
KA12	Biotite	7·22 7·25 } 7·23	(1) 1·311 (2) 1·302	8·1 8·2	212 211
	Hornblende	0·596 0·598 } 0·597	1·341	7·0	217

$\lambda_e = 0{\cdot}584 \times 10^{-10}\ \mathrm{yr}^{-1}$ $\lambda_\beta = 4{\cdot}72 \times 10^{-10}\ \mathrm{yr}^{-1}$

$K^{40} = 1{\cdot}19 \times 10^{-2}$ mole/mole K $^{*}Ar^{40}$ — radiogenic argon

intrusive rocks are gradational with thermally metamorphosed sediments and pyroclastic rocks some of which carry fragmentary Permian fossils (Mutch, 1957). The available stratigraphic information, although scanty, thus suggests a Permian or younger age for the Longwood Intrusives.

For sample KA7 the marked discordance between the biotite and hornblende dates indicates that considerable argon loss has occurred and that the hornblende age must be regarded as a minimum. In the nearby sample KA5 the hornblende age agrees with that given by the hornblende of sample KA7, suggesting that an age of about 160 m.y. may have some geological significance.

It is difficult to evaluate the single age given by the biotite of sample KA9. The indication of disturbance in sample KA7 at least as young as 162 m.y. makes it probable that the adamellite has also been affected and that the age obtained is a minimum one.

For sample KA10 the accordance of the ages for biotite and hornblende is satisfactory. In both KA10 and KA12 (*see below*), however, the measured ages of the hornblendes are a few percent greater than those of the biotites. Possibly, therefore, these rocks may have suffered some disturbance, and the measured ages should be regarded with caution and taken as minimum values.

Ruapuke Island

Little has been published on the geology of Ruapuke Island. Lithologically the rocks—mainly noritic, dioritic, and tonalitic intrusives locally carrying numerous amphibolite inclusions—are very similar to those of parts of Bluff Peninsula and the southern part of the Longwood Range. On the Stewart Island 1 : 250,000 geological map (Watters, Speden, and Wood, 1968) the greater part of Ruapuke Island is correlated with the Anglem Complex of northern Stewart Island much of which closely resembles the rocks of the southern part of the Longwood Intrusives. The biotite and hornblende ages for the Ruapuke Island tonalite (sample KA12) are accordant and similar to those for KA10.

From the Geological Society of London time scale and revisions by Webb and McDougall (1967) the measured ages obtained range from late Permian (KA3) through the middle Triassic (KA10, KA12), to the early Cretaceous (KA5, KA7). In interpreting the results, however, allowance must be made for appreciable argon loss. The most obvious cause of this is the deformation that accompanied the late Mesozoic Rangitata orogeny. If this is accepted then it could be argued that all the rocks should give the relatively young ages. Possibly, therefore, the comparatively young dates obtained are related in part to localised areas of deformation and an increase in temperature during the orogeny. The early Cretaceous and Jurassic ages obtained (Table 1) must be discarded because of the wide discordance between the biotite and hornblende determinations and the petrographic evidence of alteration, particularly in sample KA5 (*see* Appendix). Likewise the age determined on sample KA9 should be viewed with caution because of the likelihood of argon loss. However, the agreement between KA5 and KA7 hornblende results may be more than fortuitous.

If the remaining dates are accepted (KA3, KA10, KA12), then the range indicated is from 250 m.y. to 217 m.y. In the Longwood Complex and the complexes on Ruapuke Island and northern Stewart Island basic rocks are cut by diorites, tonalites, and granites. Moreover, field and petrographic evidence indicates that there have been separate episodes of intrusion of basic and probably also of granitic rocks. Thus on Stewart Island basic dike intrusion extended through most if not all of the period of igneous activity recorded there. There is, however, no field and petrographic evidence of the difference in age between the oldest and youngest intrusions, and in fact this difference may well be small. Nevertheless, the two determinations from the comparatively widely separated localities, Ruapuke Island and Kawakaputa Bay, indicate that the youngest rocks in the Longwood and Bluff–Ruapuke complexes may have been emplaced in the middle Triassic and that intrusion of the complexes as a whole extended from the Permian into the Triassic. The results obtained, however, should—until more determinations have been made—be viewed with caution because of the minor discordance between the biotite and hornblende dates.

ACKNOWLEDGMENTS

The writers wish to thank Mr J. E. R. Penman, Institute of Nuclear Sciences, Lower Hutt, for assistance during the collection of the samples, and several colleagues for helpful comments on the manuscript.

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APPENDIX

PETROGRAPHIC NOTES ON THE ROCK SAMPLES

KA3

Coarse grained hornblende gabbro grading in places to almost pure hornblendite with crystals up to 10 cm long. Minerals are pale brown hornblende and almost completely saussuritised plagioclase. The hornblende in a few places grades abruptly to an almost colourless or pale green non-fibrous variety in optical continuity with the rest. Minor reddish brown biotite is also present. Secondary minerals are widespread and include chlorite, prehnite, and actinolite. In the main the hornblende is unaffected by alteration.

KA5

Coarse grained hornblende gabbro with alternating hornblende-rich and feldspar-rich layers. Hornblende crystals are up to 4 cm long. The feldspar in the feldspathic layers (An_{70-80}) is comparatively fresh apart from minor clouding and occasional thin veins of very fine grained pale green chlorite.

In the hornblende-rich layers the feldspar is much more clouded and is considerably more albitic, approaching sodic andesine. The hornblende is mildly pleochroic (X light yellow-brown, Z brown or greenish brown). In many places it shows intense alteration and is replaced by varying relative amounts of actinolite, chlorite, and calcite.

KA7

Slightly weathered tonalite consisting of zoned andesine (55%), quartz (15%), hornblende (15%), biotite (10%), minor potash feldspar and accessory apatite, sphene, magnetite, and zircon. The ferromagnesian minerals tend to form irregular dense clusters. The larger biotite flakes have buckled cleavages in places, but otherwise the mica appears to be unaltered except for minor chloritisation.

KA9

Fine grained adamellite consisting of microperthitic orthoclase (35%), oligoclase (30%), quartz (25%), biotite (10%) and accessory magnetite and apatite. Both feldspars are densely clouded in places. Biotite is unaltered except for rare chloritisation.

KA10

Tonalite, consisting of andesine (60%), quartz (15%), biotite (15%), and hornblende (7%), with minor potash feldspar, mainly as antiperthitic inclusions within the andesine. Many of the feldspar crystals have cores densely clouded with minute inclusions, especially of sericite. Both biotite and hornblende appear to be unaltered.

The amphibolite inclusions contain andesine (50%), hornblende (25%), biotite (20%), minor quartz, and, as accessory minerals, sphene, magnetite, and innumerable tiny apatite needles.

KA12

Tonalite containing the minerals andesine (55%), quartz (15%), potash feldspar (5%), biotite (10%), and hornblende (10%), some of which encloses irregular cores of colourless augite. Biotite and hornblende tend to form irregular clusters accompanied by small irregular inclusions of quartz.

CORRECTION TO THE REPORTED OCCURRENCE OF IRON-RICH SAPONITE IN NEW ZEALAND

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ABSTRACT

Reinvestigation of the reported New Zealand occurrence of iron-rich saponite ("griffithite") from Twelve Mile Creek near Lake Wakatipu indicates that the mineral is stilpnomelane at this locality.

Iron-rich saponite (griffithite), an uncommon montmorillonite-type mineral (Ross, 1946; Faust, 1955) first reported as fillings in the amygdules of a basalt from Cahuenga Pass, Griffith Park, California (Larsen and Steiger, 1917), was reported in an epidote-rich schist of the Haast Schist Group from New Zealand. Turner and Hutton (1935, pp. 5–6) described a fine-grained red schist (OU2093) of the chlorite zone from Twelve Mile Creek, Lake Wakatipu, allegedly containing 50% epidote, 25% griffithite (iron-rich saponite), 15% quartz, and 8% hematite with accessory pennine, opaque iron ores, and calcite.

Using specimen OU3498, collected from the same locality, and illustrated by Hutton (1940, p. 56), the writer was unable to verify the refractive indices of $\alpha = 1{\cdot}498 \pm 0{\cdot}005$ and $\gamma = 1{\cdot}595 \pm 0{\cdot}005$ that were used by Turner and Hutton to identify the mineral as "griffithite". As reported by Hutton (pp. 56–57), the mineral is pseudo-uniaxial negative and strongly pleochroic with α = pale yellow to colourless and γ = fairly deep olive green, but the refractive indices obtained by the present author are $\alpha = 1{\cdot}557 \pm 0{\cdot}003$ and $\gamma = 1{\cdot}611 \pm 0{\cdot}002$. An X-ray powder photograph confirms that the so-called "griffithite" is stilpnomelane and the refractive indices correspond to a composition of 70% of the ferrostilpnomelane end member (Deer, Howie, and Zussman, 1962). Independent work by Professor C. O. Hutton (pers. comm.) substantiates this conclusion.

Recently Brown (1967, p. 286) noted that stilpnomelane and hematite seem to be mutually exclusive in metamorphic rocks. However, Hutton (1940, p. 56) ascribed the pink colour of specimen OU3498 to dustings of granular hematite. Minute hematite inclusions occur in epidote and with quartz, stilpnomelane, and chlorite form an apparently stable mineral assemblage.

A number of Japanese workers have reported iron-rich saponite in low-grade metamorphic rocks. In the green tuffs of Nagano Prefecture, Japan, it develops with laumontite (Yamagishi, 1965), and in the eastern Akaishi Mountains of Central Japan, it occurs with laumontite, analcime, mordenite, celadonite, and prehnite (Matsuda and Kuriyagawa, 1965). In a few heulandite-bearing dacite tuffs from the Southland syncline of New Zealand, deep brownish green phyllosilicates comprise a mixed-layer montmorillonite-type mineral and chlorite. This intensely coloured chlorite has a large basal spacing of 14·6 ± 0·3 Å (both untreated and glycolated). Like montmorillonite, iron-rich saponite seems restricted to rocks of the zeolite facies. Although Coombs (1961, p. 207) has predicted the occurrence of saponite, and iron-rich saponite might be expected in the zeolite facies rocks of New Zealand, the reported occurrence in higher metamorphic rocks of the chlorite zone near Lake Wakatipu is both unexpected and incorrect.

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NEW ZEALAND TRIASSIC CONODONTS

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In 1967 the writer recorded the first discovery of conodonts in New Zealand and the specimens were obtained from a Devonian Reefton limestone sample from the Waitahu River (Jenkins, 1967). The present communication is to record a conodont fauna from a well established Upper Triassic locality of Okuku limestone, Lees Pass, North Canterbury (S67/513*; grid ref. 783160).

The locality was first recorded by McKay (1877), and Hector (1881) noted *Mytilus problematicus* which was later re-identified as *Monotis calvata* Marwick, occurring with *Monotis richmondiana* Zittel (Warren *in* Fleming, 1959). According to Warren (1959 ibid.) and later Campbell and Warren (1965) the fossils indicate an Upper Triassic age (Warepan Stage of New Zealand), correlated with the international Norian Stage.

The conodont fauna has yielded 19 specimens provisionally identified as *Gondolella*, a plate-like form which has been recorded from Middle Pennsylvanian to Upper Triassic of North America, Europe, Africa, and Asia (Hass, 1962). Also present are compound bar-like conodonts. Other microfossils present in the sample include fish teeth, fish scales, and internal casts of Foraminiferida.

It is intended to carry out further investigations of Upper Paleozoic – Mesozoic limestones because it is felt that conodonts may prove invaluable for their dating.

ACKNOWLEDGMENTS

The rock sample was collected by Mr Bruce Riddolls in 1967 while in the field with Mr A. C. Beck. Miss Linda Fiddes, of this Department, treated the sample with dilute (10%) glacial acetic acid and concentrated the residue with tetra-bromoethane.

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*Fossil number in sheet S67 of the 1 : 63,360 topographical map series (NZMS 1).

GEOCHRONOLOGY OF THE BANKS PENINSULA VOLCANOES, NEW ZEALAND

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ABSTRACT

Banks Peninsula, on the central east coast of South Island, New Zealand, consists of two shield volcanoes, Lyttelton and Akaroa. Both are built mainly of mildly alkaline basaltic and andesitic lavas. Akaroa is the younger volcano and its lavas have buried much of the south-eastern part of Lyttelton. Potassium-argon dating on whole rock samples shows that Lyttelton volcano was active between about 10 m.y. and 12 m.y. ago, and that the main Akaroa activity occurred between about 8·0 m.y. and 9·0 m.y. ago. The central regions of both volcanoes have been very deeply eroded.

The Diamond Harbour Group of Liggett and Gregg (1965) consists of basaltic lavas that lie within the confines of Lyttelton volcano, and to a large extent within the erosion caldera. These lavas range from 5·8 m.y. to 8·2 m.y. in age. The oldest formation of the Diamond Harbour Group, the Church Formation, gives ages that overlap with those of the Akaroa lavas of the Mt Herbert region and are similar petrographically. This points to a possible equivalence of these lavas. The younger formations of the Diamond Harbour Group (Kaioruru and Stoddart) have considerably younger ages than the Akaroa lavas and probably were erupted from local sources. The isotopic dates, however, generally are in excellent agreement with field interpretations and indicate that volcanism in Banks Peninsula was confined to the late Miocene and the Pliocene.

INTRODUCTION

Purpose

This study was undertaken to: (1) Determine the time scale of construction and erosion of the volcanoes comprising Banks Peninsula as well as their actual age, i.e., the geological history of the volcanism. (2) Determine the history of the peninsula in relation to the Kaikoura Orogeny. (3) Further demonstrate the usefulness of whole rock lavas for K/Ar dating.

General

Banks Peninsula is located on the central east coast of South Island, New Zealand, in latitude 43° 40′ S and longitude 172° 45′ E (Fig. 1). It is elliptical in outline with major diameter (NW–SE) approximately 32 miles (51 km) and minor diameter about 20 miles (32 km). It is composed of two large shield volcanoes; Lyttelton (the older) forming the north-west sector

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and Akaroa the south-east. The volcanoes originally formed an island on the western end of the Chatham Rise (Liggett and Gregg, 1965). However, through the extension of gravel outwash forming the Canterbury Plains from the fast eroding mountains 50 miles (80 km) to the west, the north-west section of the island was connected to the mainland, forming the volcanic peninsula seen today (Liggett and Gregg, 1965).

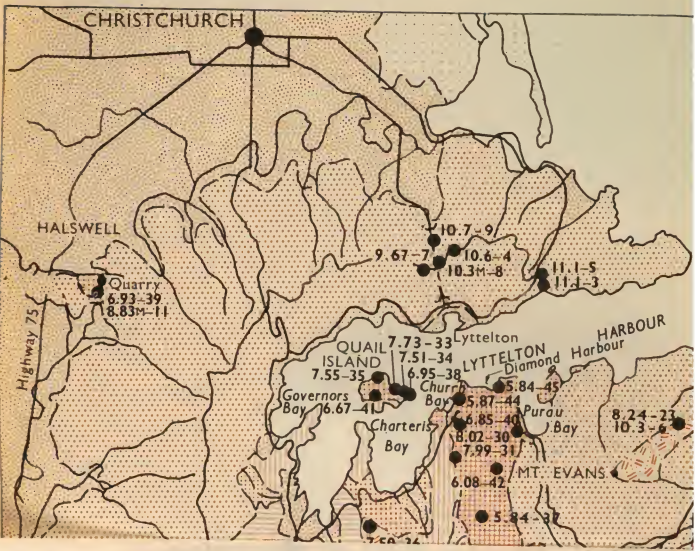
Both volcanoes are built mainly of mildly alkaline basaltic to andesitic lavas (Speight, 1924; Coombs, 1963) interbedded with an approximately equal amount of pyroclastics. The lavas of Akaroa are generally more basic than those of Lyttelton. Many of the rocks termed andesite in this paper, following the nomenclature of Speight (1924), are more closely allied to alkali andesite, such as hawaiite, than to the calc-alkaline andesites of orogenic zones. The term basaltic andesite is used in this paper for basaltic or andesitic rocks with potassium falling in the range 1·2–2·0%.

Eruptions may have occurred from fracture zones intersecting in a central vent, as in Hawaii, but the evidence to support this suggestion has been destroyed by erosion. The quaquaversal dips of the flows suggest that eruption originated dominantly from a central point for each volcano. Flows vary in thickness but generally range between 10 to 25 ft (3–8 m) with dips of 10°, flattening at high elevations to approximately 5°. Each volcano has its own system of radially oriented dikes ranging in composition from basalt to andesite to trachyte, the trachyte predominating (Speight, 1923).

Reconstructions of the original heights of the volcanoes indicate t Lyttelton reached about 5,500 ft (1,670 m) (Liggett and Gregg, 19 while Akaroa may have reached an altitude of more than 6,000 ft (1,830 (Speight, 1944). The present average altitude of Lyttelton is 1,000–1,50 with 2,300 ft (700 m) the highest point. Akaroa altitude averges *c.* 2,500 (760 m) with Herbert Peak at 3,014 ft (918 m), the highest point on t peninsula. Now long exctinct, both volcanoes are deeply dissected a characterised by large erosion calderas. The southern wall of the Akar erosion caldera is breached, and the Lyttelton wall similarly is breached the north-east, and also nearly eroded through on the south. Drowning the sea produced the present harbours and fiord-like bays around the pe pheries of the volcanoes (Speight, 1943).

Professor R. Speight, while curator of the Canterbury Museum in Chris church, was the main geological investigator of the peninsula and most o the descriptions, so heavily relied upon in this paper, are based upon hi work. Descriptions by earlier workers can be found from the reference within Speight's papers. Recent comprehensive work in the region has been done by Mr K. A. Liggett, directed primarily to the relationship of the Diamond Harbour volcanics to those of the Akaroa and Lyttelton volcanics; unfortunately little of this extensive work has been published as yet (Liggett and Gregg, 1965). Because the geology of the region is well covered in the literature mentioned, geologic descriptions will be kept to a minimum herein, but references are given for those desiring further detail.

The volcanic history of the peninsula as interpreted from the stratigraphy and K/Ar dating is discussed in the following section under four general periods of activity: (1) Basement sedimentation and pre-dome building


CHRISTCHURCH
HALSWELL
Quarry
6.93–39
8.83M–11
Highway 75
10.7–9
9.67–7
10.6–4
10.3M–8
11.1–5
11.1–3
Lyttelton
LYTTELTON HARBOUR
QUAIL ISLAND
7.73–33
7.51–34
6.95–38
7.55–35
Governors Bay
6.67–41
Church Bay
Diamond Harbour
5.84–45
5.87–44
6.85–40
8.02–30
7.99–31
6.08–42
Charteris Bay
Purau Bay
8.24–23
10.3–6
MT. EVANS
5.84–37
7.59–36

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anism including the McQueens Andesite and Gebbies Rhyolite, Lyttelton Group, (3) Akaroa Group, and (4) the Diamond Harbour up. Resurgent activity within the confines of Lyttelton volcano marks close of volcanism on the peninsula. The source of the volcanic rocks iamond Harbour, which are recognised as both later in age and generally e basic and alkaline in composition than the Lyttelton and Akaroa ups, has been uncertain for many years. Speight (1936) described them Mt Herbert flows and Quail Island flows. Liggett and Gregg (1965) ced these, plus others, into the "Diamond Harbour Group". Much of geochronological discussion of this paper is therefore devoted to this.

GEOCHRONOLOGY

Previous Estimates as to the Age of the Volcanic Activity of Banks Peninsula

That Lyttelton volcano is older than Akaroa volcano has been widely epted on the bases of geomorphology and stratigraphic relationships. vas thought to have originated from Akaroa are observed to overlie ttelton lavas, and a dike, oriented toward the centre of Akaroa, intruded ttelton flows in the Port Levy valley (Speight, 1933).

The identification of poorly preserved molluscan casts led Speight (1926) conclude that the Charteris Bay Sandstone of the Lyttelton volcano basent was Miocene. He further argued that, because considerable sedimentan and erosion occurred after the Charteris Bay Sandstone was deposited, e Lyttelton volcano was built in the later Tertiary. Speight (1944) sugsted a very late Tertiary, possibly late Pliocene age for Akaroa. Oborn d Suggate (1959) place Lyttelton as Pliocene, Akaroa as Pliocene–eistocene, and late phase volcanics within the Lyttelton erosion caldera possibly Holocene. Gage (1961) reasoned that, had Banks Peninsula isted prior to the nearby (40 miles or 64 km) early Pleistocene folding the Kaikoura Orogeny, it could hardly have escaped reflecting some of e effects of the intense folding. As there is no evidence of folding in the lcanoes, both building and dissection of them was thought to have come ter the diastrophism; the age of the volcanism was therefore regarded mid to late Pleistocene. Liggett and Gregg (1965), although implying at the volcanoes of Banks Peninsula existed prior to the Kaikoura Orogeny at were not affected by it, believed that the volcanoes were very youthful ad suggested a Pliocene age for Lyttelton, Pleistocene–Pliocene for Akaroa, ad Pliocene–Holocene for the Diamond Harbour Group.

/Ar Dating Technique

The potassium-argon dating techniques used in the Australian National niversity geochronological laboratory have been described in detail elsehere (McDougall, 1964, 1966; Cooper, 1963). Briefly, the argon is xtracted from the sample by fusion under high vacuum. The radiogenic rgon is then measured on a Reynolds type mass spectrometer using isotope ilution with Ar^{38} tracer. Potassium is determined by dissolution of a rushed rock split, mixing it with a sodium-buffered lithium solution and hen measuring it against standards on a flame photometer.

The precision of measurement must first be determined before a meaningful discussion of reliability of ages can be given. All potassium analyses were made in duplicate and values generally agreed to within 1%. Calculations on the duplicate measurements show that the standard deviation for a single measurement is ±0·4%. Argon was determined in duplicate on nine samples, and the analysis of variance indicates that the standard deviation for a single measurement is ±1·2%. Allowing a standard deviation of 0·5% for tracer calibration and combining all errors by taking the square root of the sum of the squares we obtain a standard deviation of 1·4%. Hence we believe that the overall precision of an individual K/Ar age to be approximately ±3% at the 95% level of confidence, and the errors quoted in the tables are calculated on this basis. In a few cases where the air argon contamination is particularly high (e.g., GA2032*) a greater error is recorded. Accuracy, as distinct from precision, is much more difficult to assess, but from interlaboratory comparisons (Lanphere and Dalrymple, 1967) it is believed that the ages reported in this paper are likely to be correct to better than ±5% at the 95% confidence level.

The ages measured from the Banks Peninsula volcanics are presented in Tables 2, 3, and 5 according to their probable centre of eruption; descriptions of all samples measured are presented in the appendix. The physical age of the Miocene–Pliocene boundary is in doubt until agreement is reached on the position of the Clarendonian in the geological time scale; if placed in the Pliocene the age of the boundary is about 12 m.y. (Evernden *et al.*, 1964), but if placed in the Upper Miocene then the boundary lies at about 7 m.y. (Funnell, 1964). The ages in this paper are referred to the physical time scale of Funnell (1964), who assigns an age of about 7 m.y. to the Miocene–Pliocene boundary.

Reliability of Ages

The time since extrusion and crystallisation of a volcanic rock can be determined by K–Ar dating to within the limits imposed by experimental error and uncertainties in the decay constants, provided that the rock has remained a closed system since crystallisation, i.e., there has been no loss or gain of potassium or radiogenic argon other than by radioactive decay. A further assumption is that at the time of extrusion all pre-existing radiogenic argon contained in the magma was lost. The only means of judging whether the underling assumptions are fulfilled is by the consistency or otherwise of the results.

McDougall (1964) and Dalrymple (1963) showed that whole rock samples of volcanic rocks give reliable dates provided that the samples are free of alteration as determined by examination of a thin section. In some cases it appears that fine grained alteration products do not retain radiogenic argon even at normal temperatures (cf. Webb *et al.*, 1967), although Amaral *et al.* (1966) and McDougall *et al.* (1966) demonstrated that deuteric alteration may not be as serious a problem as initially thought. In this study all samples were examined in thin section; only rocks with no or minimal alteration have been used, except where specifically noted.

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*GA is the laboratory sample number prefix.

Pre-Lyttelton Volcanics and Basement

In the Gebbies Pass region at the head of Lyttelton Harbour (Fig. 1) erosion has nearly breached the southern flank of the volcano, exposing pre-Lyttelton Group rocks rising to 1,000 ft (305 m) above sea level. The formations and their relationships to one another (Speight, 1935) are summarised in Table 1.

TABLE 1—Summary of the Stratigraphy in the Lyttelton Area

Unit	Age	Relationships
Lyttelton Group	Miocene (this paper)	Group
		unconformity
Gebbies Rhyolite	(?)Miocene (Speight, 1935)	Formation
		unconformity
Charteris Bay Sandstone	(?)Miocene (Speight, 1935)	Formation
		unconformity
McQueens Andesite	(?)Oligocene (this paper)	Formation
		unconformity
Basement Greywackes	(?)Triassic (Oborn and Suggate, 1959)	Group

The pre-Lyttelton volcanics are minor in volume compared to the Lyttelton Group. The McQueens Andesite crops out on Thompsons Spur and Gold Spur in McQueens Valley near Gebbies Pass and it represents an early phase of volcanism in the area stratigraphically controlled by the underlying (?)Triassic greywackes and overlying (?)Miocene Charteris Bay Sandstone. A Cretaceous age was suggested (Speight, 1935), based on the lithological similarity with andesites whose stratigraphic positions are more precisely known in the Malvern and Clent Hills to the west. K/Ar dating of a sample from the side of Thompsons Spur gave an age of 32·5 m.y. This sample (Ref. No. 1, Table 2 and Fig. 1) is an andesite, dark and vitreous in hand specimen. Thin section examination showed it to be quite fresh and unaltered. However, because none of the other samples collected from this formation was of suitable freshness, no other measurements could be made as a consistency check. Therefore, until confirmatory dates can be obtained, 32·5 m.y., corresponding to the early Oligocene, should be regarded as a reliable minimum.

The Gebbies Rhyolite, described in detail by Speight (1922), is white in colour and cryptocrystalline, with large phenocrysts of smoky quartz and sanidine. Two attempts were made to date sanidine from this formation near Governors Bay but the ages were aberrant and not reproducible at 9 m.y. and 10·8 m.y. Because the formation is considered on stratigraphic grounds to be definitely pre-Lyttelton Group, argon loss is indicated, as shown by the Lyttelton Group dates reported in the next section. The folding of the basement (Speight, 1935), may have caused this loss of radiogenic argon

TABLE 2—Potassium-argon Ages from the Lyttelton Volcano

Map Ref. No.	GA No.	Material	%K	$^{40}Ar^{*}/^{40}K \times 10^{-4}$	$\%^{40}Ar$ Atm	Calculated Age ($\times 10^{6}$ yr)	General Location
11	2008	Basalt	$\left.\begin{matrix}0·680\\0·678\end{matrix}\right\}0·679$	5·18	66·4	8·83 (M)	Halswell Quarry (columnar)
7	2007	Trachyte	$\left.\begin{matrix}4·365\\4·361\end{matrix}\right\}4·365$	5·66	12·3	9·67 ± 0·29	Bridal Path dike
6	2006	Andesite	$\left.\begin{matrix}2·080\\2·084\end{matrix}\right\}2·082$	6·06	7·4	10·3 ± 0·3	Mt Evans
5	2005	Andesite	$\left.\begin{matrix}2·012\\2·038\end{matrix}\right\}2·020$	6·50	27·1	11·1 ± 0·3	Harbour Quarry
4	2004	Basalt	$\left.\begin{matrix}0·855\\0·865\end{matrix}\right\}0·860$	6·19	30·0	10·6 ± 0·3	Summit Road
8	2178	Trachyandesite	$\left.\begin{matrix}3·120\\3·072\end{matrix}\right\}3·096$	6·06	72·5	10·3 (M)	Lyttelton Tunnel
9	2177	Basalt	$\left.\begin{matrix}0·787\\0·782\end{matrix}\right\}0·785$	6·27	28·7	10·7 ± 0·3	Lyttelton Tunnel
3	2003	Basalt	$\left.\begin{matrix}1·020\\1·034\end{matrix}\right\}1·027$	6·53	63·6	11·1 ± 0·3	Harbour Quarry
2	2002	Basalt	$\left.\begin{matrix}0·651\\0·655\end{matrix}\right\}0·653$	6·70	32·2	11·9 ± 0·4	Gebbies Pass
1	2001	Andesite	$\left.\begin{matrix}1·661\\1·653\end{matrix}\right\}1·657$	19·14	31·0	32·5 ± 0·8	Thompson's Spur

Decay Constants $\lambda_{\beta} = 4·72 \times 10^{10} yr^{-1}$, $\lambda e = 0·585 \times 10^{-10} yr^{-1}$. $^{40}K = 1·19 \times 10^{-2}$ atom %.

(M) = Minimum age only. $^{40}Ar^{*}$ = Radiogenic Argon. Atm = Atmospheric.

Lyttelton Group

On the bases of geomorphology and stratigraphy, Lyttelton has been considered the older of the Banks Peninsula volcanoes. Andesitic lavas are more common than in the predominantly basaltic Akaroa (Speight, 1924). In general the Lyttelton rocks are somewhat deuterically altered, and consequently fewer acceptable samples were found and dated from this volcano.

Sample GA2002 (2), stratigraphically the lowest collected, occurs as a flow approximately 200 ft (61 m) above the base of the Lyttelton Group near Gebbies Pass (Fig. 1) and gave the oldest age for the volcano at 11·9 m.y. Specimen GA2007 (7), stratigraphically the youngest, is a trachyte dike cutting some of the highest flows on the Lyttelton east rim (Speight, 1938), and gave the youngest age at 9·7 m.y. The dike is oriented toward the centre of the volcano (Quail Island), and therefore provides some evidence that the volcanic shield was not markedly eroded at this time. All other samples from Lyttelton were collected from stratigraphically intermediate positions and gave ages between 10·3 m.y. and 11·1 m.y. The dates on samples GA2177 (9) and GA2178 (8) are not in proper stratigraphic sequence, although statistically the ages overlap. GA2178 in thin section (*see* Appendix) has some groundmass alteration and probably has experienced some degree of argon loss. GA2003 (3) and GA2003 (5) are from the Harbour quarry approximately 2 miles (3·2 km) east of the town of Lyttelton. They are fairly low stratigraphically and give concordant ages of 11·1 m.y. GA2006 (6) from the highest exposed Lyttelton lavas on Mt Evans on the west side of Port Levy Valley gave an age of 10·3 m.y. GA2008 (11) from Halswell quarry will be discussed in the section covering the Diamond Harbour Group volcanics. Volcanism in Lyttelton volcano continued from about 11·9 m.y. to 9·7 m.y. ago, a period of approximately 2 m.y. during the late Miocene. Although there are no ages lying between 11·9 m.y. (GA2002) and 11·1 m.y. (GA2003), this apparent 0·8 m.y. gap is probably because of the general paucity of suitable samples, rather than to any real break in volcanic activity.

Akaroa Group

The oldest dates measured on Akaroa lavas are 9·0 m.y. (Table 3). Sample GA2009 (13) was obtained from a lava at sea level in Akaroa Harbour and GA2010 (14) is from a lava dipping gently northward near sea level at the head of Pigeon Bay (Fig. 1). Both lavas are stratigraphically low in the volcano.

A sample from the Monument (Fig. 1, GA2001, 15) gave an age of 8·95 m.y. As the Monument is a prominent feature at about 2,300 ft (700 m) above sea level, on the south flank of Lyttelton, its old age would appear to be anomalous. However, the age may indicate that eruption of lavas during the early dome-building phase of Akaroa was very rapid; the precision of measurement is such that a period of 0·1 m.y. to 0·3 m.y. for the build up could be envisaged.

The youngest age found for Akaroa was 8·0 m.y. (GA2024, 28) from a basaltic lava stratigraphically high in the sequence in the Le Bons Bay region on the eastern flanks of the volcano (Fig. 1).

TABLE 3—Potassium-argon Ages from the Akaroa Volcano

Map Ref. No.	GA No.	Material	%K	$^{40}Ar^*/^{40}K \times 10^{-4}$	$\%^{40}Ar$ Atm	Calculated Age ($\times 10^6$ yr)	General Location
36	2032	Basalt	$\left.\begin{matrix}1\cdot170\\1\cdot160\end{matrix}\right\}1\cdot165$	4·40	91·6	7·50 ± 0·50	Tableland Spur
32	2028	Andesite	$\left.\begin{matrix}2\cdot071\\2\cdot059\end{matrix}\right\}2\cdot065$	4·84	8·6	8·2 ± 0·19	Te Oka Road
29	2025	Basalt	$\left.\begin{matrix}0\cdot954\\0\cdot955\end{matrix}\right\}0\cdot955$	4·67 4·72	15·3 8·0	7·97 8·06 ± 0·15	Mt Herbert
28	2024	Basalt	$\left.\begin{matrix}0\cdot777\\0\cdot782\end{matrix}\right\}0\cdot780$	4·74 4·68	85·2 87·4	8·09 8·00 ± 0·20	Le Bons Bay
27	2023	Basaltic Andesite	$\left.\begin{matrix}1\cdot531\\1\cdot534\end{matrix}\right\}1\cdot533$	4·77	24·8	8·14 ± 0·24	Herbert Peak
25	2021	Basalt	$\left.\begin{matrix}1\cdot227\\1\cdot260\\1\cdot231\end{matrix}\right\}1\cdot239$	4·79	33·5	8·18 ± 0·24	East Rim
24	2020	Basalt	$\left.\begin{matrix}0\cdot562\\0\cdot562\end{matrix}\right\}0\cdot562$	4·82	63·2	8·22 ± 0·25	Herbert Peak East
17	2012	Basalt	$\left.\begin{matrix}1\cdot203\\1\cdot202\end{matrix}\right\}1\cdot202$	4·82	58·6	8·23 ± 0·26	Little River South
23	2018	Basaltic Andesite	$\left.\begin{matrix}1\cdot397\\1\cdot399\end{matrix}\right\}1\cdot398$	4·83	19·7	8·24 ± 0·25	Mt Evans Outlier
22	2017	Basaltic Andesite	$\left.\begin{matrix}1\cdot626\\1\cdot621\end{matrix}\right\}1\cdot623$	4·85	5·6	8·28 ± 0·25	Kaituna Lagoon

TABLE 3—*continued*

21	2016	Basaltic Andesite	1·653 1·672	1·662	4·91	11·8	8·38 ± 0·25	Okains Bay
20	2015	Basalt	1·182 1·187	1·184	4·93	16·3	8·41 ± 0·25	Wainui Quarry
19	2014	Basaltic Andesite	1·426 1·416	1·421	5·01	15·8	8·55 ± 0·26	SE Trig ZZ, Herbert
18	2013	Basalt	1·094 1·097	1·095	5·03	45·1	8·58 ± 0·26	Kaituna
16	2019	Gabbro-Biotite	6·855 6·890	6·872	5·23 5·23	43·8 44·0	8·92 8·92 ± 0·13	Onawe Peninsula
15	2011	Basalt	1·176 1·180	1·178	5·20 4·29	11·7 26·7	8·88 9·02 ± 0·18	Monument
14	2010	Basaltic Andesite	1·696 1·691	1·694	5·29	55·5	9·02 ± 0·27	Pigeon Bay
13	2009	Basalt	0·766 0·759	0·763	5·16 5·33	81·9 83·4	8·81 ± 0·26 9·23 ± 0·27	Wainui Headland
12	2174	Syenite- Alkali feldspar	4·007 4·052	4·032	6·94	32·6	11·8	Onawe Peninsula

All samples were processed as whole-rock except where specifically indicated otherwise.

Table 3 shows an almost continuous spectrum of ages measured on lavas from various localities in the volcano. Where stratigraphy is known with some certainty the ages are consistent; e.g., GA2028 (32) is stratigraphically about 600 ft (180 m) higher than GA2012 (17), and the ages agree to within experimental error.

Samples from the Mt Herbert and Herbert Peak region (locality no. 19), 24, 27, 29) yield ages lying between 8·0 m.y. and 8·5 m.y. These dates are within the same age range as those measured on many of the lavas from the main Akaroa dome (Fig. 1); there is little question that the activity in the two regions was contemporaneous. It is uncertain whether the Mt Herbert – Herbert Peak lavas which are essentially flat-lying were erupted from Akaroa, flowed north-west and were ponded in the Mt Herbert area, or were erupted locally.

A similar age of 8·2 m.y. was found for a lava overlying Lyttelton volcanics on the summit of Mt Evans (Fig. 1); this flow was mapped as an Akaroa outlier by Liggett and Gregg (1965). The ages on the volcanic rocks from Herbert Peak, Mt Herbert and Mt Evans show that the south-east flank of Lyttelton volcano was blanketed by these lavas about 8·5 m.y. to 8·0 m.y. ago.

Sample GA2032 (36) from Tableland Spur, south of Charteris Bay (Fig. 1), gave an age of 7·5 m.y. ± 0·5 m.y. Tableland Spur consists of flat-lying lavas regarded by Speight (1917) as belonging to Lyttelton Group, but Liggett and Gregg (1965, fig. D–3) map the lavas as probable Akaroa Group. The age obtained supports the latter interpretation. Mr K. A. Liggett (pers. comm.) believes that the Tableland Spur lavas are continuous with those of Mt Herbert but that they are stratigraphically lower. The measured ages are not necessarily in conflict with this view when the large uncertainty of the date on GA2032 is taken into account. However, the age on the Tableland Spur sample does agree with dates of the earlier lavas on Quail Island in Lyttelton Harbour, to be discussed in a later section.

The possibility of a volcanic episode prior to the main Akaroa dome building phase has been discussed by Speight (1940). An attempt has been made to test his suggestion and although only partially successful, it merits some discussion here. His evidence for such a phase centres chiefly on the area at sea level around the head of Akaroa harbour and particularly on Onawe Peninsula. On the basis of dike orientation, Onawe Peninsula appears to be the volcanic centre suggesting that the "plutonic" gabbro and syenite cropping out there could represent an exposed early intrusive phase. However, Speight also recognised the alternative that the "plutonics" are the slowly cooled portion of the magma from which the basaltic dome and trachyte dikes were derived. The contact relationship of the gabbro to the syenite is obscured. Just north of the peninsula the gabbro is interpreted to intrude basaltic lava, indicating activity prior to emplacement of the gabbro. Biotite extracted from the gabbro (GA2019, 16) gave an age of 8·92 m.y., indicating contemporaneity with the first rapid surge of activity which produced the bulk of the dome. Alkali feldspar extracted from the syenite (GA2174, 12) gave an age of 11·8 m.y., apparently 3 m.y. older than any other igneous rock dated from Akaroa, and also similar in age to the earliest Lyttelton Group. However, the syenite is very open textured with numerous drusy cavities, mostly unfilled, indicating that crystallisation probably occurred in the presence of a considerable gas pressure, argon undoubtedly a component. McDougall has noted widely aberrant intraformational ages from a syenite of similar field occurrence in Réunion. Thus, until an independent sample from the Onawe syenite body can be obtained and measured, the 11·8 m.y. age must be regarded with suspicion; its older age is possibly due to the presence of excess argon (cf. Livingston *et al.*, 1967).

On the data now available, Akaroa presents a geochronological picture of intense volcanic activity about 9·0 m.y. ago, with rapid building to at least 2,300 ft (700 m, indicated by the Monument, GA2011) above present sea level. Activity then waned and some of the basaltic magma slowly crystallised in the volcano throat to give the gabbro of Onawe (GA2019). Intermittent activity continued and a second peak of activity occurred between about 8·5 m.y. and 8·0 m.y. ago, when large volumes of lava were erupted blanketing the whole southern flank of Lyttelton volcano and possibly pouring over into its erosion caldera.

Diamond Harbour Group

Occurring entirely within the confines of the original Lyttelton volcano are isolated areas of olivine basalt of a somewhat more alkaline composition. These lavas generally are flat-lying and apparently are valley fills, and are clearly younger than the Lyttelton Group.

Speight (1933) suggested that the lavas seen to have flowed into Diamond Harbour (Fig. 1) had a common source (Akaroa) with those of the high flat-lying lava beds of Mt Herbert. The basaltic lavas on Quail Island he considered to be of local origin and the youngest in age (Speight, 1936). Liggett and Gregg (1965), after extensive stratigraphic and petrographic investigations, showed that the flows of Diamond Harbour could be traced up to the south-east wall of the Lyttelton erosion caldera and indicated local points of eruption just to the north of Herbert Peak. They agreed with Speight that lavas of Quail Island were local in origin. Liggett and Gregg (1965) created the Diamond Harbour Group which included olivine basalt cropping out: (*a*) within the Lyttelton erosion caldera at Purau Bay, Diamond Harbour, Church Bay, and Quail Island; (*b*) outside the caldera at Halswell Quarry, Ahuriri, Kaituna Valley, and Port Levy Valley (these are indicated in Liggett and Gregg, 1965, fig. D–3). Their subdivision of the basalts at Diamond Harbour and Quail Island, on the basis of petrography, is summarised in Table 4.

Considerable effort was expended in dating the Diamond Harbour Group to determine, if possible, the probable sources of these lavas. Dates were obtained from all of the areas of outcrop of the Diamond Harbour Group with the exception of those in Kaituna Valley. The ages are presented in Table 5, summarised in Table 6, and discussed individually below.

(1) *Diamond Harbour*

These lavas were shown by Liggett and Gregg (1965, fig. D–3) to extend from an altitude of 1,800 ft (550 m) on the south-east erosion caldera wall of Lyttelton volcano to below sea level at Diamond Harbour and Church Bay.

Sample GA2026 (30) from a road cutting in the Church Formation at Purau Bay gave an age of 8·03 m.y., identical to GA2025 (29) from Mt Herbert (Fig. 1). The outcrop was columnar and massive and in thin section the sample was fresh. A sample from the Church Formation of suitable freshness for dating was not found in the Church Bay area itself.

Sample GA2036 (40) was collected from the Kaioruru Formation overlying the Church Formation in the Church Bay road cutting. This sample was fresh and suitable for dating, although in general it is difficult to find unaltered rocks from this formation. The indicated age was 6·85 m.y., approximately 1 m.y. younger than the underlying Church Formation.

Four samples were measured from separate localities in the Stoddart, the youngest formation of the Diamond Harbour Group; GA2041 (45) near sea level at Diamond Harbour; GA2040 (44) from the road cutting at Church Bay; GA2038 (42) from a valley side exposure approximately 1·5 miles (2·4 km) south-east of Diamond Harbour at 1,000 ft (300 m) altitude; and GA2033 (37) at 1,500 ft (492 m) altitude. GA2041, GA2040, GA2038, and GA2033 gave ages of 5·84 m.y., 5·87 m.y., 6·08 m.y., and 5·84 m.y. respectively, all in excellent agreement.

GA2027 (31) was obtained from Castle Rock, a knob standing alongside the south side of the Stoddart flows just discussed, and at approximately 750 ft (220 m) altitude, 1 mile (1·6 km) south of Church Bay (Fig. 1). K/Ar dating places the Castle Rock at 7·99 m.y., very similar to the Church Formation and Mt Herbert lavas, suggesting that it is an erosional remnant.

(2) *Quail Island*

Cliffs 200 ft (61 m) high on the north side of Quail Island provide excellent exposures of the pre-Kaioruru Formations. Samples GA2029 (33) and GA2030 (34) came from massive horizontal flows on the north side of the island and gave ages of 7·73 m.y. and 7·51 m.y. respectively. GA2029 was collected *in situ* near the base of the lower flow but GA2030 was from a large block which had apparently fallen from the upper flow. GA2034 (38) taken from lavas interpreted to have flowed against and buried a cliff cut into the pre-Kaioruru horizontal flows (Liggett and Gregg, 1965)

TABLE 4—Summary of Liggett and Gregg's Diamond Harbour Group Subdivisions

Diamond Harbour	Quail Island	General Characteristics
Stoddart Formation	post-Kaioruru	Abundant olivine phenocrysts with less common pyroxene. Irregular jointing.
Kaioruru Formation	Kaioruru	Doleritic groundmass with olivine phenocrysts. Irregular jointing.
Church Formation	pre-Kaioruru	Olivine phenocrysts with less common pyroxene and plagioclase in fine grained groundmass. Columnar jointing in many localities.

TABLE 5—Potassium-argon Dates from the Diamond Harbour Group

Map Ref. No.	GA No.	Material	%K	$^{40}Ar^*/^{40}K$ $\times 10^{-4}$	$\%^{40}Ar$ Atm	Calculated Age ($\times 10^6$ yr)	General Location
45	2041	Basalt	0·892 0·893 } 0·893	3·42	25·0	5·84 ± 0·17	Diamond Harbour—Stoddart Formation
44	2040	Basalt	0·865 0·870 } 0·868	3·44	34·4	5·87 ± 0·17	Church Bay—Stoddart Fm.
43	2039	Basalt	0·859 0·847 } 0·853	3·57	58·2	6·03 ± 0·18	Port Levy—Stoddart Fm.
42	2038	Basalt	0·882 0·887 } 0·885	3·56	45·4	6·08 ± 0·18	Flow—Diamond Harbour Region. Stoddart Formation
41	2037	Basalt	0·732 0·730 } 0·731	3·98 3·85	22·1 12·6	6·76 6·58 ± 0·20	Quail Island, post-Kaioruru Formation
40	2036	Basalt	1·085 1·086 } 1·085	4·01	51·0	6·85 ± 0·20	Church Bay—Kaioruru Fm.
39	2035	Basalt	0·987 0·976 } 0·982	4·06	26·5	6·93 ± 0·20	Halswell Quarry (platy)
38	2034	Basalt	0·952 0·952 } 0·952	4·07	39·0	6·95 ± 0·20	pre-Kaioruru (cliff burying)
37	2033	Basalt	1·012 0·010 } 1·011	3·42	35·5	5·84 ± 0·15	2·5 miles south of Diamond Harbour
34	2030	Basalt	1·070 1·062 } 1·066	4·40	53·4	7·51 ± 0·22	Quail I., upper North (pre-Kaioruru Formation)
35	2031	Basalt	1·197 1·182 } 1·190	4·48	39·8	7·55 ± 0·23	Quail I., NW (pre-Kaioruru)
33	2029	Basalt	1·120 1·118 } 1·119	4·52	38·5	7·73 ± 0·23	Quail I., lower North (pre-Kaioruru Formation)
26	2022	Basalt	0·947 0·949 } 0·948	4·79	26·5	8·18 ± 0·24	Ahuriri
31	2027	Basaltic Andesite	1·654 1·650 } 1·652	4·68	32·0	7·99 ± 0·19	Castle Rock
30	2026	Basalt	1·296 1·284 } 1·291	4·72 4·68	62·7 53·3	8·05 7·99 ± 0·20	Purau Bay

TABLE 6—Summary of Ages of Basalts from the Diamond Harbour Group

	Formations of Liggett and Gregg (1965)	General Location	Sample No.	Age Years $\times 10^6$
Diamond Harbour	Stoddart	2·5 miles SE of Harbour	2033	5·84
		1·5 miles SE of Harbour	2038	6·08
		Road cutting, Church Bay	2040	5·87
		Sea level, Diamond Harbour	2041	5·84
	Kaioruru	Road cutting, Church Bay	2036	6·85
	Church	Road cutting, Purau Bay	2026	8·03
	post-Kaioruru	Trig HH	2037	6·67
Quail Island	Kaioruru			
	pre-Kaiouru	Cliff-burying lavas	2034	6·95
		Island west side	2031	7·55
		Upper(?) flow NW cliffs	2030	7·51
		Lower flow NW cliffs	2029	7·7

yielded an age of 6·95 m.y. Flat-lying Kaioruru flows can be clearly seen to overlie this lava unconformably in one small area; however, no samples of the Kaioruru could be obtained that were suitably fresh for dating. GA 2037 (41) from the post-Kaioruru near Trig HH, the highest point on the island, was measured in duplicate providing an age of 6·67 m.y. This is almost 1 m.y. older than its suggested Stoddart equivalent at Diamond Harbour and Church Bay. This could mean either that the Stoddart Formation erupted over a long period of time or, that the Stoddart Formation and post-Kaioruru are derived from local centres at independent points in history. It should be noted that although we were unable to date the Quail Island Kaioruru marker lava, the underlying sample GA2934 dated at 6·95 m.y., and the overlying post-Kaioruru lava (GA2037) dated at 6·67 m.y. provide strict limits on its time of eruption, and that these narrow limits are in excellent agreement with the 6·85 m.y. age (GA2036) obtained from the Kaioruru Formation at Church Bay. One further sample, collected from the west side of the island (GA2031), was isolated by surrounding soil cover and could only be identified as pre-Kaioruru. Table 6 presents a geochronological summary of the Diamond Harbour Group within the Lyttelton erosion caldera.

(3) *Halswell Quarry*

This area on the west flank of Lyttelton has been described in detail by Speight (1924, 1936). Originally this locality was a landmark by virtue of a parasitic cone standing approximately 300 ft (100 m) above the surrounding area. Years of quarrying have completely removed the cone and dug deep into the spur beneath the cone exposing two periods of volcanic activity. Near the present quarry back (west side) columns of a somewhat altered basalt are overlain by a thin bed of pyroclastics. Overlying the pyroclastics and extending into the eastern quarry section is an olivine basalt flow, considered on petrographic grounds (Liggett and Gregg, 1965) to be part of the Diamond Harbour Group. This basalt is platy, and occurs in large spheroidally weathered blocks.

Samples were taken from both the platy olivine basalt (GA2035, 39) and the underlying columnar basalt (GA2008, 11), giving ages of 6·93 m.y. and 8·83 m.y. respectively. The former was fresh and suitable for K/Ar dating; however, the latter contained a considerable amount of groundmass and mineral alteration. Processing of GA2008 was carried out only to provide an indication of minimum age. GA2035, therefore, is definitely Diamond Harbour Group in age (Kaioruru Formation age-equivalent) and GA2008 is probably main-phase Lyttelton Group which has since experienced some argon loss because of the extensive alteration.

(4) *Ahuriri*

A columnar olivine basalt lava flow forms a prominent, but isolated, feature standing about 25 ft (7·6 m) above farm land approximately 200 yd (180 m) south of Highway 75 on the south side of Lyttelton volcano (Fig. 1). Speight (1924) noted that basalts from this area were petrographically similar to those of Quail Island and Halswell Quarry. Liggett and Gregg (1965) included the Ahuriri lava flow within the Diamond Harbour Group on the basis of petrography. Sample GA2022 (26) yielded an age of 8·18 m.y., indicating that if related to the Diamond Harbour Group it stands out as the oldest measured. However, the date is within the age range of Akaroa; possibly this lava is a product of Akaroa local activity.

(5) *Port Levy*

Near the head of Port Levy Valley (Fig. 1) are two large spurs composed of flat-lying lava flows petrologically very similar to the Stoddart Formation (Mr K. A. Liggett, pers. comm., 1967). Also the same rock type crops out locally toward the valley mouth along the north side near sea level. Although Liggett and Gregg (1965, fig. D–3, p. 14) diagrammatically included these rocks in Diamond Harbour Group, no description has yet been published.

Sample GA2039 (43) was collected from the eastern spur and yielded an age of 6·02 m.y., correlating closely in age with the Stoddart Formation at Diamond Harbour. The date of this valley fill is important, for, when considered with the age of the Mt Evans (Akaroa) outlier at 8·24 m.y., the two provide a maximum time of about 2·2 m.y. for eroding out the valley to something near its present volume. This will be discussed further in a later section.

SUMMARY AND CONCLUSIONS

Volcanism

The Banks Peninsula area has been the locus of intermittent volcanism of varying intensity of activity for at least the period ranging from middle Oligocene (this paper) to early or middle Pliocene. The earliest volcanic activity is represented by the McQueens Andesite at 32·5 m.y., followed somewhat later by the Gebbies Rhyolite. Their volumes, however, are insignificant when compared with the main dome building volcanism of Lyttelton and Akaroa. From the isotopic ages presented in this paper, a general sequence of events has been reconstructed and is discussed below. A summary is presented in Table 7.

The building of the volcanic shield at Lyttelton began about 12 m.y. ago and reached its maximum (reconstructed) height of approximately 5,000 ft (1,525 m) about 9·7 m.y. ago; an active period of approximately 2 m.y. Akaroa volcano became active about 9 m.y. ago and quickly (0·2–0·3 m.y.) built to a height of at least 2,300 ft (700 m), as now represented by the Monument (an erosional remnant) on the south-east flank of the Lyttelton

TABLE 7—Geochronological Summary of Banks Peninsula Volcanic Events
(Ages in m.y.)

Major Grouping	Beginning	Termination	Phase	
Diamond Harbour Group	6·7	5·8†	Stoddart Formation	
	6·9	6·8	Kaioruru Formation	
	8·0	7·5	Church Formation and pre-Kaioruru	
Mt Herbert Region	8·5	8·0	2nd Phase	Akaroa Activity
	9·0	9·0	1st Phase	
Akaroa	9·0*	8·0†	Main Dome	
Lyttelton	11·9*	9·7†	Main Dome	

*Oldest measured but probably began somewhat earlier.
†Youngest measured but probably ended somewhat later.

volcano. Akaroa activity, although fairly continuous elsewhere, appears to have waned in the south Lyttelton region, until a resurgence of activity occurred between 8·5 m.y. and 8·0 m.y. ago. These lavas blanketed much of the south-eastern flank of Lyttelton, and from the 8·0 m.y. dates obtained on the Purau Bay (GA2026, 30) and Castle Rock (GA2027, 31) lavas of the Diamond Harbour Group it is deduced that the younger Mt Herbert lavas may have overtopped the south-east rim of the already eroded Lyttelton caldera and flowed northward into Diamond Harbour.

It is not clear whether the pre-Kaioruru Formation basalts of the Diamond Harbour Group on Quail Island in Lyttelton caldera that give slightly younger ages of 7·7 m.y. and 7·5 m.y. (GA2029, 33; GA2030, 34) are similarly related to the Mt Herbert flows or whether they were erupted from local vents.

The Kaioruru Formation of the Diamond Harbour Group was erupted 6·8 m.y. ago on to an erosional surface cut into the older Diamond Harbour Group basalts. On Quail Island the flows immediately preceding and following the defined Kaioruru Formation basalt give essentially the same age. The younger flow at Halswell quarry on the north-west flank of Lyttelton was also erupted at this time. Outpouring of the Stoddart Formation olivine basalts of the Diamond Harbour Group brought volcanism to a close on Banks Peninsula about 5·8 m.y. ago. The Kaioruru and younger flows were produced from localised vents.

In general, the ages presented in this paper support the conclusions made by previous workers concerning the relative time sequence of volcanic events, the chief difference being the considerably older overall age which places the initiation of main volcanism in the late Miocene and termination of activity about middle Pliocene.

Erosion

Physical overlap of the volcanic centres has placed age limits on stages of erosion such that some comment can be made regarding rates of dissection.

The trachyte dike (GA2007) high on the north rim of Lyttelton volcano was probably injected near the end of Lyttelton activity (Speight, 1936), its position and orientation suggesting that little erosion had taken place by 9·7 m.y. ago. Across Lyttelton Harbour, Church Formation flows at Purau Bay (GA2026) dated at 8·0 m.y. indicated that erosion of Lyttelton level occurred within the period of about 1·7 ± 0·5 m.y., forming an erosional caldera more than 11 miles long. Further, erosion of Akaroa and Lyttelton lavas sufficient to produce a valley the size of the present Port Levy valley occurred between 8·24 m.y. and 6·02 m.y.; this is indicated by the Mt Evans outlier (GA2018) of Akaroa age and the Port Levy valley-fill lavas of the Diamond Harbour Group. Thus, Miocene Lyttelton and Akaroa erosion rates are probably roughly comparable in allowing marked shield dissection over a period of about 2 m.y.

Taking 1·7 m.y. ± 0·5 m.y. as the length of time for maximum erosion of 4,000 ft (1,200 m) depth, the rate of denudation of Lyttelton volcano calculates to about 28 m (70 cm)/1,000 yr, a rather high rate of removal, roughly comparable to Papua (Ruxton and McDougall, 1967). Speight

(1924) noted, however, that on the Lyttelton Summit road the pyroclastics constitute two-thirds of the erupted material. This, combined with high relief, would facilitate a high rate of denudation.

The amount of erosion which both Lyttelton and Akaroa suffered within a period of 1·5 m.y. – 2·0 m.y. in the late Miocene – early Pliocene, seems to contrast sharply with the relatively small degree of erosion which has apparently occurred on the Peninsula since the end of volcanism, almost 6 m.y. ago. Neither Lyttelton Harbour nor Port Levy valley appear much larger now, than when they were invaded by lava flows from their neighbouring centres of eruption. Two possible explanations can be offered; (1) the climate of the late Miocene had much higher rainfall than that of the Pliocene and Pleistocene or (2) a considerable rise in relative sea level occurred which greatly reduced the amount of stream energy available for wider dissection. The first suggestion is difficult to evaluate but definite evidence for the second exists in the form of cores from wells drilled near Christchurch. These wells intersected layers of peat down to 450 ft (137 m) below sea level before striking Lyttelton lavas more than 700 ft (224 m) below sea level (Speight, 1943). Relative sea level may have risen, therefore, some 700 ft. Whether this was due to a real sea level rise or to subsidence of the volcanoes after cessation of eruption is not known.

Kaikoura Orogeny

The Kaikoura Orogeny formed the Alpine mountains and is considered to have reached its climax shortly after the onset of the first climatic deterioration in the late Cenozoic. This was recognised by Gage (1961) who showed that glacial till is steeply folded in the Ross area of Westland, South Island. Dating of basalts, interpreted to have erupted just after the first cooling, indicates that this cooling occurred about 2·5 m.y. ago (Stipp, Chappell, and McDougall, 1967; Mathews and Curtis, 1966), thus indicating the Kaikoura climax was more recent than 2·5 m.y. ago. The absence of folding in Banks Peninsula is presumably related to its position on the west end of the Chatham Rise (Liggett and Gregg, 1965); the volcanoes were either close to, but structurally separated from, the line of folding or they acted as a competent mass. Volcanism had apparently ceased about 4 m.y. before the climax of the Kaikoura Orogeny.

Whole Rock Dating

The usefulness of whole rock lava for K/Ar dating has been further demonstrated in this study, by the consistency of the results. Further, the several measurements made on the Diamond Harbour Group show that geological mapping can be successfully carried out through geochronology using carefully selected samples. However, it is an expensive method.

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APPENDIX

SAMPLE DESCRIPTIONS AND LOCALITIES

1 GA2001[*] Andesite, S84/012345[†], Thompsons Spur in McQueens Valley. Abundant phenocrysts of plagioclase and pyroxene are set in a groundmass of fine grained plagioclase and pyroxene with interstitial glass. All components fresh, and glass isotropic.

2 GA2002 Basalt, S84/991384, 1·5 miles north of junction of Gebbies Pass on Summit Road. Abundant olivine and pyroxene phenocrysts set in a holocrystalline groundmass of plagioclase, pyroxene, and iron oxide. Occasional amygdaloidal material.

3 GA2003 Basaltic andesite, S84/107482, Lyttelton Harbour quarry about 1·5 miles east of Lyttelton, petrographically similar to GA2002 but considerable green chloritic material and altered olivine.

4 GA2004 Basalt, S84/075491. Road cutting on Summit Road overlooking Christchurch just above railway tunnel entrance. Similar to GA2002.

5 GA2005 Andesite, S84/107482, same location as GA2003 except that it is from a higher flow. Holocrystalline and fine grained. Occasional completely altered olivine and some greenish infilling.

6 GA2006 Andesite, S84/155435. Just below Akaroa outlier contact on Mount Evans (approx. 100 ft lower than GA2018): plagioclase, pyroxene, and occasional olivine, all fresh.

7 GA2007 Trachyte, S84/067484. Vertical dike on Summit Road near Bridle Path above tunnel; rare large phenocrysts of alkali feldspar in holocrystalline trachytic groundmass of feldspar. Fresh.

8 GA2178 Trachyandesite, S84/071487. Lyttelton tunnel flow 4,100 ft from Heathcote portal. Submitted by Mr S. Nathan. Fresh plagioclase laths in trachytic groundmass with moderate alteration. Minimum age only.

9 GA2177 Basalt, S84/068498, Lyttelton tunnel, 580 ft from Heathcote portal. Submitted by Mr S. Nathan. Fresh rocks with small areas of chloritic material.

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[*] GA is the laboratory sample number prefix.

[†] Grid reference based on the sheet districts of the 1:63,360 topographical map series (NZMS 1) and the national thousand-yard grid shown on this series.

11	GA2008	Basalt, S84/952476. Massive columnar section in back of Halswell quarry. Stratigraphically below GA2035. Considerable alteration of groundmass. Minimum age only.
12	GA2174	Syenite (K-feldspar), S94/254260. Near south end of Onawe Peninsula, west side. Open textured rock with common drusy cavities. Fairly widespread alteration throughout the feldspars.
13	GA2009	Basalt, S94/240215. Outcrops on Wainui Headland at sea level. Stratigraphically some of lowest rocks sampled. No olivine, plagioclase fresh. Considerable greenish chloritic material associated with about 10% of the pyroxenes. Considerable calcite is present. Argon extraction required aliquoting technique to handle the large amount of CO$_2$ generated from the calcite. Minimum age only.
14	GA2010	Basaltic andesite, S84/227368. Small abandoned quarry on road at head of Pigeon Bay, 10 ft above sea level. Holocrystalline. Fine grained, fresh.
15	GA2011	Basalt, S84/122382. Boulder from talus at base of Monument on Purau – Port Levy road. Holocrystalline and fresh.
16	GA2019	Gabbro (biotite), S94/253262, from west side of Onawe Peninsula.
17	GA2012	Basalt, S94/136232. Road cut on Kinloch road between Little River and Wainui. Altitude 1,100 ft. Similar petrographically to GA2010. Occasional chloritic material associated with the pyroxenes. In general fresh.
18	GA2013	Basalt, S94/008263. Highway 75 road cutting near Lake Ellesmere. Slightly vesicular. Holocrystalline, fresh plagioclase and pyroxene. Olivine completely iddingsitised.
19	GA2014	Basaltic andesite, S84/110355. One-quarter mile south-east of Trig ZZ. Fresh plagioclase, lesser pyroxene, and rare olivines.
20	GA2015	Basalt, S94/240235. Small quarry on Wainui road. Material possibly from a dike. 300 ft altitude. Holocrystalline; plagioclase, pyroxene, and olivine fresh.
21	GA2016	Basaltic andesite, S85 pt S95/365373. Road cutting between Okains Bay and Little Akaloa. Holocrystalline, fine grained and fresh.
22	GA2017	Basaltic andesite, S94/032242. Large road cutting on Highway 75 beside Kaituna Lagoon. All minerals fresh.
23	GA2018	Basalt, S84/155435. Near base of Akaroa outlier on Mt Evans, altitude 1,000 ft. All minerals, including olivine, fresh.
24	GA2020	Basalt, S84/108357. 200 yd south-east of Trig ZZ, Herbert Peak area. Plagioclase crystals show preferred orientation. All minerals fresh.
25	GA2021	Basalt, S94/292171. Road cutting on Lighthouse Road on east rim of Akaroa. Altitude 2,000 ft. Olivine, plagioclase, and pyroxene fresh.
26	GA2022	Basalt, S84/938343. Ahuriri—knob of columnar basalt standing in paddock, 200 m south of Highway 75. Abundant large phenocrysts of olivine in fine grained holocrystalline groundmass of plagioclase and pyroxene. Fresh.
27	GA2023	Basaltic andesite, S84/092367. 60 ft above cliff forming ridge between Mt Herbert and Herbert Peak. Rare olivine. Fine grained equigranular. Fresh.
28	GA2024	Basalt, S85 pt S95/351293. Road cutting between Le Bons Bay and Okains Bay. Altitude 1,500 ft. No olivine. Considerable amygdaloidal infilling. In few places plagioclase is slightly altered.
29	GA2025	Basalt, S84/072358. Next to top flow of Mt Herbert. Altitude 2,550 ft. Holocrystalline and equigranular with abundant olivine. Very fresh.
30	GA2026	Basalt, S84/099433. Road cutting south-west side of Purau Bay. Altitude 20 ft. Columnarly jointed. Holocrystalline. Flow oriented plagioclase. Olivine uncommon. Plagioclase predominant and fresh. Church Formation.

31	GA2027	Basaltic andesite, S84/077419. Castle Rock, standing along south-west side of Diamond Harbour Group flows near Trig II. Strongly jointed. Abundant plagioclase, lesser pyroxene and uncommon olivine. Fresh.
32	GA2028	Andesite, S94/132210. Te Oka road cutting near junction with Kinloch road. Altitude 1,800–1,900 ft. Abundant flow oriented plagioclase and intersertal pyroxene and uncommon olivine. Fresh.
33	GA2029	Basalt, S84/054445. Near base of lower massive, columnar, horizontal flow of Quail Island north-west cliff face. Fresh plagioclase, pyroxene, and olivine. Occasional small areas of devitrified glass in groundmass. Pre-Kaioruru Formation.
34	GA2030	Basalt, S84/055444. Similar to GA2029 except from very large block fallen from one of the two horizontal flows (apparently the upper). Abundant unaltered phenocrystic olivine. Fresh plagioclase and pyroxene. Few small areas of devitrified glass in groundmass. Pre-Kaioruru Formation.
35	GA2031	Basalt, S84/047446. North-west side of Quail Island, isolated columnar jointed cliff exposure. Common very large, partly altered, pyroxene phenocrysts. Considerable fresh glass in groundmass. Pre-Kaioruru Formation.
36	GA2032	Basalt, S84/047400. North end of Tableland Spur, uppermost flow. Altitude 940 ft. Randomly oriented phenocrysts of plagioclase, pyroxene, and olivines set in a fine grained groundmass of plagioclase and pyroxene. Fresh, but occasional amygdaloidal infilling.
37	GA2033	Basalt, S84/088402. Prominent feature on spur leading 2·5 miles of Diamond Harbour at 1,500 ft (492 m) altitude. Fresh and holocrystalline.
37	GA2034	Basalt, S84/058443. Flow burying a cliff cut into flows of GA2029 GA2030. Large phenocrysts of olivine. All minerals fresh but some areas of devitrified glass in groundmass. Pre-Kaioruru Formation.
39	GA2035	Basalt, S84/952476. Near the entrance of Halswell quarry. Platy jointing. Stratigaphically overlies columnar basalt GA2008. Fresh.
40	GA2036	Basalt, S84/078438. Kaioruru Formation from road cutting at Church Bay. Almost doleritic texture; finely vesicular. Holocrystalline and fresh. Kaioruru Formation.
41	GA2037	Basalt, S84/050442. From Post Kaioruru Formation at Trig HH, the highest point on Quail Island. Holocrystalline with all minerals fresh.
42	GA2038	Basalt, S84/090415. Prominent bluff on left side of creek leading down to Diamond Harbour. Altitude 1,000 ft. Fresh with only minor iddingsitisation of olivines. Stoddart Formation.
43	GA2039	Basalt, S84/170400. North end of east spur in Port Levy Valley. Similar to GA2037 in mineralogy and texture. Very fresh except for incipient iddingsitisation of olivine. Stoddart Formation.
44	GA2040	Basalt, S84/079435. Road cutting on east side of Church Bay. Typical Stoddart Formation. Holocrystalline and fresh.
45	GA2041	Basalt, S84/091445. Diamond Harbour at sea level. Petrographically similar to GA2040, but finer grained and olivine mostly iddingsitised. Stoddart Formation.

STRATIGRAPHY OF HUTCHINSONIAN AND AWAMOAN STAGES (LOWER MIOCENE) AT TARGET GULLY, OAMARU, NEW ZEALAND

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ABSTRACT

Globigerinoides trilobus trilobus (Reuss) and *Globorotalia zealandica zealandica* Hornibrook, previously considered to appear in the Awamoan Stage, are reported from Hutchinsonian beds at Target Gully, Oamaru. Trends in the lineages of *Haeuslerella pukeuriensis* Parr and *Globigerinoides trilobus trilobus* (Reuss) are used to estimate relationships between the sequence at Target Gully and the name bearers of Otaian, Hutchinsonian, and Awamoan Stages. The *"Pachymagas"* shellbed at Hutchinson's Quarry lies at, or slightly above the Otaian–Hutchinsonian boundary; higher units of the Hutchinsonian are present at Target Gully. The name bearer for the Awamoan Stage may correlate with beds beneath Target Gully Shellbed, the base of the stage by original designation.

INTRODUCTION

The shellbed at Target Gully, Oamaru (Marshall and Uttley, 1913; Gage, 1959), is famous for its molluscan assemblage; its significance in middle Tertiary stratigraphy, due to its designation as base of the Awamoan Stage by Thomson (1916), has been neglected since the revision by Allan (1933). Development of the foraminiferal biostratigraphy of the Hutchinsonian and Awamoan Stages of Thomson by Finlay and Marwick (1940, 1947) was based on faunas from the implied name-bearing localities (Hutchinson's Quarry and Awamoa Creek). At neither locality is superposition of the two stages demonstrable. This leaves open the question of the relation of foraminiferal criteria for the stages to the Hutchinsonian–Awamoan boundary originally set by Thomson. In this respect the sequence beneath the shellbed at Target Gully is critical.

This paper records the sequence seen in a shallow channel excavated in May 1966, and the ranges of index Foraminifera. Trends in the foraminiferal lineages of *Haeuslerella pukeuriensis* Parr and *Globigerinoides trilobus trilobus* (Reuss) are used to correlate the section with name bearers for Otaian, Hutchinsonian, and Awamoan Stages.

LITHOSTRATIGRAPHY

Park (1918, fig. 35) recorded the section (*see* Table 1) in Target Gully near the Town Belt.

The column in Fig. 1 elucidates (b) of Park's section and applies the lithostratigraphic nomenclature of Gage (1957). Weathered tuffs (Deborah Volcanic Formation) are succeeded by a thin bed of rubbly semi-crystalline limestone (? McDonald Limestone). Park's unit (b) and the lower part

Table 1—Section in Target Gully, Near the Town Belt, Oamaru, Recorded by Park (1918, fig. 35)

Top (ft)		
	Surface clays and gravels	(f)
6·0	Target Gully Shellbed	(e)
2·0–4·0	Hard yellowish brown glauconitic sandstone	(d)
	Soft glauconitic sandstone fossiliferous	(c)
	Obscured	(b)
	Well bedded olive green tuffs	(a)
Bottom		

of (c) represent Gee Greensand. Basaltic conglomerate (Ardgowan Conglomerate) and the *"Pachymagas"* bed, prominent basal units of this formation at Hutchinson's Quarry, 0·5 mile to the south, were not observed. The transition from Gee Greensand to Rifle Butts Formation is gradational. In the field the boundary was placed 10–12 ft below the base of Target Gully Shellbed. This was checked by laboratory analysis of glauconite content of both formations: the transition seen in the field corresponds to a zone in which glauconite declines to less than 10% by weight of the fraction held on a sieve with 0·076 mm opening (Fig. 1). Comparable results were obtained for samples from the Gee Greensand – Rifle Butts Formation contact at "Old Rifle Butts", type locality of the latter unit. Beds above Target Gully Shellbed are deeply weathered: lower horizons of Park's (f) may belong to Rifle Butts Formation.

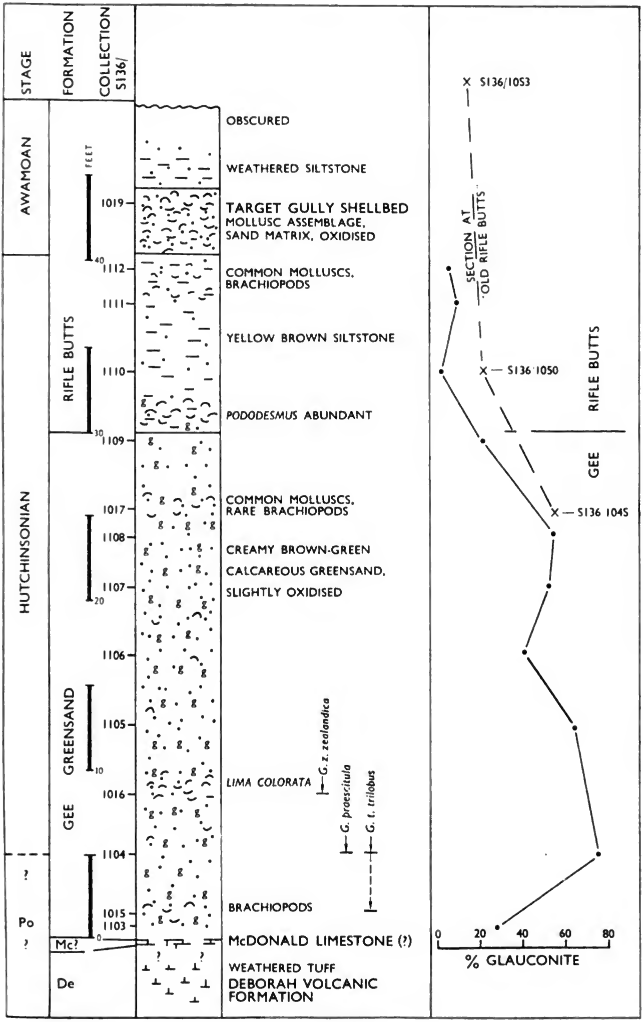
RANGES OF AWAMOAN INDEX FORAMINIFERA

Hornibrook (1959) cited species that define the boundary between Hutchinsonian and Awamoan Stages according to the implicit revision by Finlay and Marwick (1947). The Awamoan was recognised by the first appearances of:

Globorotalia miozea Finlay "small and atypical" (= *G. praescitula* Blow)
G. cf. *miocenica* Palmer (= *G. zealandica zealandica* Hornibrook)
Globigerinoides trilobus (Reuss)
Loxostomum n. sp. (= *L. pakaurangiense* Hornibrook)

Subsequently Hornibrook (1961) reported *Globorotalia miozea* (small var.) from Gee Greensand at Hutchinson's Quarry (S136/819), name-bearer for Hutchinsonian and *Loxostomum pakaurangiense* from Otaian strata in Northland (N18/569). *Globigerinoides trilobus trilobus* and *Globorotalia zealandica zealandica* are present at the name-bearing locality for Awamoan Stage (Awamoa Creek). They have been used as criteria for, or correlation with Awamoan by Geiger (1962), Jenkins (1967), and Walters (1965); see also Scott (1968).

Fig. 1—Stratigraphic column for sequence below Target Gully Shellbed, Oamaru (S136/539678, prov. edition 1943). Glauconite percentages refer to amount extracted (by Franz separator) from fraction of disaggregated sample held on sieve with opening of 0·076 mm. The trace for samples from section at "Old Rifle Butts" (same scale) shows change across Gee Greensand : Rifle Butts Formation boundary set by Gage (1957).


STAGE
FORMATION
COLLECTION S136/
AWAMOAN
HUTCHINSONIAN
?
Po
?
RIFLE BUTTS
GEE GREENSAND
Mc?
De
FEET
40
30
20
10
0
1019
1112
1111
1110
1109
1017
1108
1107
1106
1105
1016
1104
1015
1103
OBSCURED
WEATHERED SILTSTONE
TARGET GULLY SHELLBED
MOLLUSC ASSEMBLAGE,
SAND MATRIX, OXIDISED
COMMON MOLLUSCS,
BRACHIOPODS
YELLOW BROWN SILTSTONE
PODODESMUS ABUNDANT
COMMON MOLLUSCS,
RARE BRACHIOPODS
CREAMY BROWN-GREEN
CALCAREOUS GREENSAND,
SLIGHTLY OXIDISED
LIMA COLORATA
G. z. zealandica
G. praescitula
G. t. trilobus
BRACHIOPODS
McDONALD LIMESTONE (?)
WEATHERED TUFF
DEBORAH VOLCANIC FORMATION
X S136/1053
SECTION AT 'OLD RIFLE BUTTS'
X — S136/1050
X — S136 1045
RIFLE BUTTS
GEE
0
20
40
60
80
% GLAUCONITE

Target Gully Shellbed is the basal horizon of the Awamoan Stage by original designation (Thomson, 1916). The sequence beneath this bed enables the ranges of Awamoan index species to be checked against Thomson's Hutchinsonian–Awamoan boundary. Because of inadequate exposures and lack of explicit stratal definition this is not possible at the name-bearing localities.

Globigerinoides trilobus trilobus appears to arise from *G. trilobus altiaperturus*; the branching process is shown by changes in distribution of the ratio of height/width of the primary aperture. Populations with a single mode (broadly elliptical aperture) are followed by those with a bimodal distribution, or at least a shift towards lower values of the ratio (low, elongate aperture). This pattern has been noted in Northland, New Zealand, Trinidad, and in south-western France (Scott, in press). The lowest record of the lineage in Target Gully section is S136/1015, 1·5–2·0 ft above the base of Gee Greensand. Here, the shape of primary aperture is variable but the sample is inadequate to show divergence of *G. trilobus trilobus*. However, this is demonstrated in the succeeding sample, S136/1104 (Fig. 2, histogram). Here the marked primary mode represents specimens with low aperture (*G. trilobus trilobus*) and the secondary mode those with high apertures (*G. trilobus altiaperturus*). S136/1104 is taken as the lowest definite record of *G. trilobus trilobus* (Figs. 3, 4) in the section. This identification views *G. trilobus trilobus* as a population arising by a shift of modal variation in shape of the primary aperture. Antecedent populations may have a few specimens, near the lower tail of the distribution, that could be identified, by morphotype, as *G. trilobus trilobus*.

Similarly, the lowest record of *Globorotalia zealandica zealandica* (S136/1016, Figs. 5, 6) marks a point in gradational and changing populations. At this level variation in chamber arrangement and ventral inflation of the test is judged, qualitatively, to overlap with that seen in populations from Rifle Butts Formation from which the species was described (S137/499, Pukeuri, Oamaru). The population in S136/1016 may be less advanced than that in S137/499.

The basal horizon (S136/1103) of the Gee Greensand is Otaian (*Ehrenbergina* of the *healyi, willetti, marwicki* group and *Haeuslerella pukeuriensis* lineage). S136/1015, 1 ft higher, is probably still Otaian as judged by the *H. pukeuriensis* lineage, whereas the population in S136/1104, 3 ft above S136/1015 is post-Otaian and possibly more advanced than that

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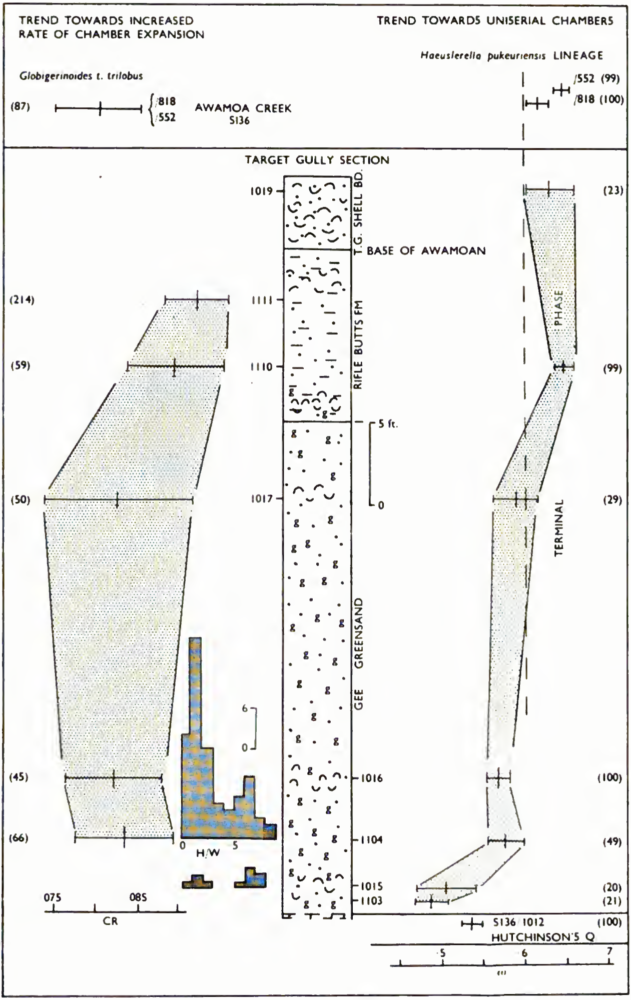
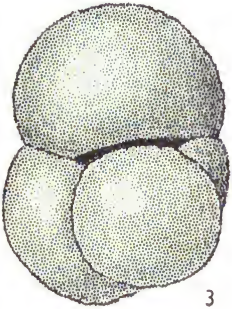
FIG. 2—Target Gully section: histograms show distribution of height/width ratios for primary aperture, *Globigerinoides trilobus* lineage in basal horizons of Gee Greensand. The primary mode in S136/1104 represents *G. t. trilobus*. Means and 95% confidence limits are shown (on left) for trend towards increase in rate of chamber expansion in *G. t. trilobus* (*G. t. altiaperturus* excluded according to distribution of height/width ratios for primary aperture). Only specimens with intact final chamber and in which the diameters of the last three chambers (Dn–2, Dn–1, Dn) obey the relation $Dn \geqslant Dn-1 \geqslant Dn-2$ are included. Values are shown as $\log_{10}$ common ratio. Position of measurements is shown in Scott (1966, fig. 3). In the trend towards uniserial chambering in *Haeuslerella pukeuriensis* lineage (right) "terminal phase" refers to stabilisation of trend : mean values 0·60–0·66. Results for Awamoa Creek (both lineages) and Hutchinson's Quarry (*Haeuslerella*) shown for comparison.


TREND TOWARDS INCREASED RATE OF CHAMBER EXPANSION
TREND TOWARDS UNISERIAL CHAMBERS
Haeuslerella pukeuriensis LINEAGE
Globigerinoides t. trilobus
(87)
/818
/552
AWAMOA CREEK
S136
/552 (99)
/818 (100)
TARGET GULLY SECTION
1019
T.G. SHELL BD.
BASE OF AWAMOAN
(23)
(214)
1111
RIFLE BUTTS FM
PHASE
(59)
1110
(99)
5 ft.
0
(50)
1017
(29)
TERMINAL
GEE GREENSAND
6
0
(45)
1016
(100)
(66)
0
H/W
5
1104
(49)
1015
1103
(20)
(21)
075
085
CR
S136 1012
(100)
HUTCHINSON'S Q
5
6
7

from immediately above the *"Pachymagas"* bed at Hutchinson's Quarry. The lowest record of *Globorotalia praescitula* in Target Gully section is in S136/1104 (Figs. 7, 8).

As subsequent workers have not modified Thomson's placement of the Hutchinsonian–Awamoan boundary at the base of Target Gully Shellbed, these data lead to rejection of remaining foraminiferal criteria for its recognition elsewhere. However, it may be argued that the names "Hutchinsonian" and "Awamoan" are available for use with new faunal criteria provided that name-bearing localities and definitional horizons (e.g., Target Gully Shellbed) fall within the revised stage concepts and that homotaxy with adjacent stages is satisfied. Stratigraphic relationships of horizons of nomenclatural importance are now examined.



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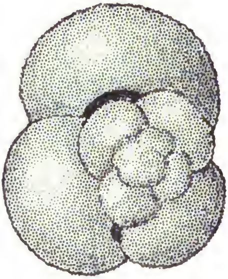

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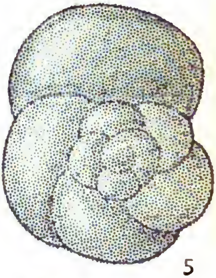

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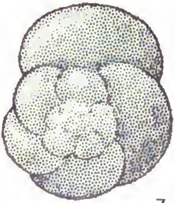

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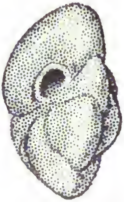
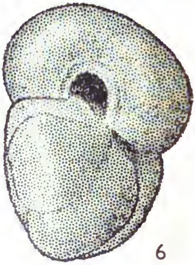


8



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R. C. Brazier del.

FIGS. 3, 4—*Globigerinoides trilobus trilobus* (Reuss). S136/1104, Target Gully. N.Z.G.S. Cat. No. FP2026, FP2027.

FIGS. 5, 6—*Globorotalia zealandica zealandica* Hornibrook. S136/1016, Target Gully. N.Z.G.S. Cat. No. FP2025.

FIGS. 7, 8—*Globorotalia praescitula* Blow. S136/1104, Target Gully. N.Z.G.S. Cat. No. FP2024. (all × 140)

RELATION BETWEEN OTAIAN AND HUTCHINSONIAN NAME-BEARERS

Scott (1965) considered that the trend towards uniserial chamber arrangement in *Haeuslerella* was more advanced in populations from Hutchinson's Quarry than in a sample from uppermost Otaian at the name-bearing locality, Bluecliffs, South Canterbury (S119/506). This result was based on pooled samples from several horizons in the quarry and required testing against localised collections. To avoid the sedimentary complexity of the quarry face (Gage, 1957, p. 84) excavations were made a few yards to the south-east. Here, Ardgowan Conglomerate is overlain by 14 ft of greensand (Eden Greensand Member, Fig. 9). Haeuslerellas are common only in an horizon 7 ft above the base of this member (S136/1012), immediately above a well defined brachiopod shellbed, here called, informally, the *"Pachymagas"* shellbed. Use of the ω-model (Scott, 1965) to compare this population ($M_\omega = 0{\cdot}538$) with S119/506 ($M_\omega = 0{\cdot}523$) indicates that the difference between means may be due to random fluctuations in sampling ($t = 1{\cdot}614$, $0{\cdot}2 > P > 0{\cdot}1$). As significant advance towards uniserial chambering in S136/1012 over S119/506 cannot be demonstrated it appears that the top of the *"Pachymagas"* shellbed correlates with, or is very slightly higher than the upper Otaian boundary at Bluecliffs. S136/821 (entered in N.Z. Geological Survey register of foraminiferal collections as "type Hutchinsonian greensands, with typical brachiopods . . . obtained by digging into bank") may be a collection from the *"Pachymagas"* shellbed; the sample mean ($M_\omega = 0{\cdot}532$) approximates that for S136/1012. Other samples pooled by Scott (1965) have slightly higher sample means and appear to come from the face of the quarry. However, the sample with the highest value (S136/819, $M_\omega = 0{\cdot}562$ "soft conglomerate matrix probably associated with the hard limestone") cannot be shown to differ significantly from S136/1012 ($t = 1{\cdot}538$, $0{\cdot}2 > P > 0{\cdot}1$). The only record of *Globorotalia praescitula* from Hutchinson's Quarry is in S136/819 (Hornibrook, 1961).

The *"Pachymagas"* shellbed was not recognised in Target Gully section; beds equivalent to uppermost Otaian and the shellbed, as judged by the sequence of populations of *Haeuslerella* (Fig. 2) are either condensed into the interval between S136/1015 and S136/1104, or missing. No evidence of disconformity was seen in the field.

RELATION BETWEEN HUTCHINSONIAN AND AWAMOAN NAME-BEARERS

Two populations of *Haeuslerella* were examined from Awamoa Creek: S136/552 is from the mouth of the creek, immediately below a hard concretionary horizon, and S136/818 is located 10–15 chains upstream from the mouth. The trend towards uniserial chamber arrangement is markedly more advanced in both samples (S136/552, $M_\omega = 0{\cdot}646$; S136/818, $M_\omega = 0{\cdot}616$) than in populations from Hutchinson's Quarry (Fig. 9 shows the comparison with S136/1012) and suggests that the localities are stratigraphically distinct. The difference between the mean values for samples from Awamoa Creek is highly significant ($t = 3{\cdot}549$, $0{\cdot}01 > P$) but may not indicate stratigraphic disparity: in the terminal phase of the trend, mean values have

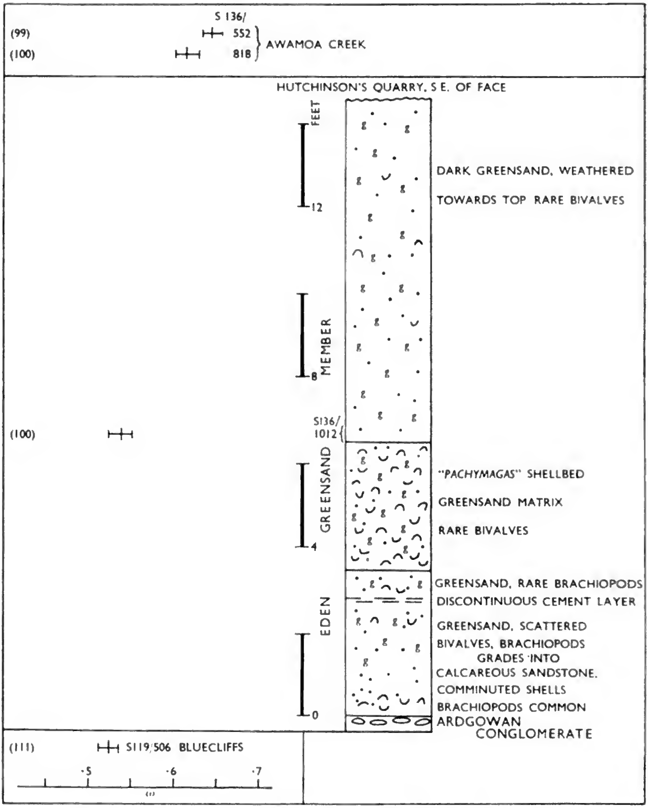

FIG. 9—Stratigraphic column for Hutchinson's Quarry, Oamaru, south-east of quarry face (S136/538666, prov. edition 1943). Mean and 95% confidence limits for *Mω*, index of trend towards uniserial chambers in *Haueslerella pukeuriensis* lineage (Scott, 1965) shown for sample from top of *"Pachymagas"* bed. Populations from uppermost Otaian (Bluecliffs) and from Awamoa Creek shown for comparison. Size of sample shown in brackets.

been found to fluctuate within the range 0·60–0·66. It is unknown whether this faithfully reflects the pattern of variation in the lineage or indicates a defect in the model used to estimate progress towards uniserial chambering.

RELATION BETWEEN AWAMOAN NAME-BEARER AND TARGET GULLY SHELLBED

Increase in rate of chamber expansion, estimated by the common ratio of the geometric series for diameter of the antepenultimate and final chambers, is a major trend in *Globigerinoides trilobus trilobus* after its divergence from *G. trilobus altiaperturus.* Details of measurements are given by Scott (1966). Figure 2 shows that, in terms of this trend, primitive populations occur in Target Gully section from S136/1104 to S136/1017 (Gee Greensand): there is no appreciable increase in mean values. More advanced populations occur in samples from Rifle Butts Formation beneath Target Gully Shellbed.

Mean values of the common ratio in S136/552 and S136/818, Awamoa Creek, are identical (compare result for *Haeuslerella* lineage). The pooled value compares with those from Gee Greensand at Target Gully rather than with S136/1110 and S136/1111 from Rifle Butts Formation (Fig. 2). The significant difference between mean values for S136/1111, 2 ft below Target Gully Shellbed, and the Awamoa Creek sample suggests that the horizons at the Awamoan name-bearer correlate with beds *below* the surface that Thomson designated as base of the Awamoan Stage.

This result can only be partially checked by the trend towards uniserial chambering in *Haeuslerella.* Populations from Target Gully Shellbed and Awamoa Creek are at the terminal phase of the trend ($M_\omega \geqslant 0{\cdot}60$); this may also apply to S136/1017, 5 ft below top of Gee Greensand in Target Gully section ($M_\omega = 0{\cdot}588$, $t_{0{\cdot}05}s\ (M_\omega) = 0{\cdot}026$) but lower samples appear not to have reached this phase. Stratigraphically, this suggests that the horizons at Awamoa Creek are unlikely to correlate with beds at Target Gully below S136/1017.

CONCLUSION

Planktonic Foraminifera used to distinguish Awamoan from Hutchinsonian in terms of the stage revision by Finlay and Marwick (1947) occur beneath the bed designated as basal Awamoan by Thomson. Awamoan correlations based on the presence of *Globigerinoides trilobus trilobus, Globorotalia zealandica zealandica,* or *G. praescitula* are suspect.

The sequential relation of Otaian and Hutchinsonian name-bearers, implied by Finlay and Marwick (1947) is confirmed. Strata at Awamoa Creek are considered to be stratigraphically superior to those at Hutchinson's Quarry but not necessarily to the shellbed at Target Gully.

ACKNOWLEDGMENTS

Messrs P. A. Maxwell and D. P. Batchelor assisted with field work, and the latter performed the glauconite separations. Dr N. de B. Hornibrook and Mr P. A. Maxwell reviewed the manuscript.

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LETTER TO THE EDITOR

LOESS DEPOSITS AND GLEYED HORIZONS IN OKARITO SOILS OF NORTH AND SOUTH WESTLAND

Sir,

This letter is prompted by a recent paper by Young (1967), dealing with loess deposits of the west coast of the South Island of New Zealand. During the course of extensive field and laboratory investigations of soils in the Franz Josef region, including soils near Okarito in south Westland, the writer has formed some impressions which may supplement Young's observations.

In his paper (p. 650) Young stated, with reference to depositional surfaces formed during the Otira Glaciation in north Westland, that (*a*) the distribution of loess on $K2_{(1)}$ terraces is very restricted; (*b*) no loess occurs on $K2_{(2)}$ surfaces at Nelson Creek, the Ahaura Plain, and near Kumara Junction;* (*c*) no loess has been recognised on terraces formed during or since the K3 advances of the Otira Glaciation; and (*d*) loess has not been recognised on any surface south from Lake Mapourika, because there are no visible pre-Otira Glaciation terraces landward of the present coastline in this area. Okarito and Waiuta soils have developed within loess capping $K2_{(1)}$ terraces in north Westland, and ". . . the association of thick loess deposits with the Okarito and Waiuta soils of the high terraces is clearly established" (p. 657). However, Young also stated that the presence of 1–6 ft of loess was not the only, or in some cases even the major, cause of the formation of gleyed soils. The intention of this letter is to describe some features of gleyed horizons within Okarito soils in the type area in south Westland, which has no loess.

Many soils within a few miles east of Okarito township broadly resemble the Okarito fine sandy loam described by Gibbs *et al.* (1950) and/or the Okarito peaty loam reported by Wells (1962) and Gibbs (1964), both of which were developed within loess-capped fluvioglacial terraces near Hokitika (*see* fig. 4 in Gibbs, 1964). On the other hand, Okarito soils west of Lake Mapourika have developed within approximately 3 ft of moderately compact ablation moraine overlying an extremely compact basal till. Below the soil profile the contact between the moraine and till is commonly sharp and cemented by a thick continuous iron pan. None of the four criteria used by Young to characterise the loess deposits of north Westland (p. 648) applies to blue-grey sandy loam gleyed horizons within Okarito soils near Okarito in south Westland. For instance, such horizons are not of uniform thickness, and do not conform to the topography of the underlying gravels. Soil catenas very similar to those described by Crampton (1965) are common in the undulating moraine-and-kettle topography near Okarito, providing strong evidence that varying thicknesses of gleyed horizons are related to topographic position and pedogenetic processes, rather than to layers of loess. Slopes steeper than about 10° rarely exhibit blue-grey sandy loam gleyed horizons near the surface, while areas of low relief in valleys or on plateaux usually have gleyed horizons of considerable thickness underlying a metre or more of peat. The horizons commonly contain rounded quartz pebbles up to 3 cm in longest dimension, and many scattered quartz chips about 1 cm in length, presumably weathered from stones and boulders of schist. Pseudomorphs of these boulders are occasionally seen within the gleyed horizons. The pebbles and chips may comprise up to 2% of the weight of soil excavated from these horizons. No data are available for grain size, sorting, and skewness of these soil materials, but results of mechanical analyses by the pipette method do not remotely resemble results in Young's fig. 3 (p. 653), even allowing for slightly different size classes and analytical methods. Coarse plus fine sand (2·0–0·02 mm) comprises 63·5% and 67·6% of organic matter-free material smaller than 2 mm in gleyed horizons of two soils near Okarito, while silt (0·02–0·002 mm) comprises 26·4% and 21·9% and clay (less than 0·002 mm) 10·13% and 10·48%. On these data it seems unlikely the gleyed horizons are composed of loessial deposits.

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*A misprint on p. 650 of Young's paper attributes these surfaces to the $K2_{(1)}$ glacial advance.

The writer agrees with Young that iron pans and cemented gravel are poorly developed within many Okarito and Waiuta soils, and can rarely be regarded as the principal cause of saturation in overlying gleyed horizons. The permeabilities reported by Young for six samples of loess (about 10^{-6} cm/sec) must restrict water movement where loess forms surface gleyed horizons. In the absence of loess, another reason for the permanent saturation of the gleyed horizon may lie in the mechanism proposed by Crompton (1956). These soils invariably possess a thick surface layer of greasy mor-like organic matter, which promotes and sustains anaerobic conditions in the underlying gleyed horizon.

Young demonstrated the common occurrence in north Westland of thin layers of loess on $K2_{(1)}$ terraces bearing Okarito soils. Gibbs (1950) mapped Kumara loam on the loess free $K2_{(2)}$ terrace west of Kumara township, but this soil is not as leached as Okarito fine sandy loam (Gibbs, p. 13) and is probably younger. Okarito soils on $K2_{(1)}$ surfaces east of Hokitika have developed in loess capping the fluvioglacial gravels, and therefore differ from Okarito soils on loess-free $K2_{(2)}$, or possibly $K2_{(1)}$, surfaces under a higher rainfall further south. While none of the statements in this note contradict the sense of Young's paper, which dealt principally with north Westland, it is perhaps relevant to make the following conclusions:

(*a*) In south Westland the combination of narrow river valleys, low wind velocities, and very high rainfall probably precluded the formation of much or any loess.

(*b*) The parent materials of Okarito soils in north Westland differ physically from parent materials of their counterparts in south Westland.

(*c*) There may be some grounds for reclassifying Okarito soils, to distinguish between those developed in loess over fluvioglacial gravels, and those not so developed.

(*d*) Okarito soils do not seem to occur in north Westland on terraces younger than $K2_{(1)}$ age, whereas in south Westland a mature Okarito profile may be formed in as little as 20,000 years ($K2_{(2)}$ surfaces).

(*e*) Gleyed loess-like materials present in south Westland Okarito soils are not eolian in origin, but are the product of some 20,000 yr of pedogenesis under a super-humid climate.

I am grateful to Mr D. J. Young, Dr R. P. Suggate, and Professor T. W. Walker for their critical comments on the information presented and views expressed in this letter.

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30 April 1968.

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LETTER TO THE EDITOR

SEISMICITY AND STRUCTURE IN SOUTH-WEST NEW ZEALAND AND THE MACQUARIE RIDGE

Sir,

In his recent paper, basically discussing magnetic measurements south-west of Fiordland, Hatherton (1967) illustrated the Fiordland region with a map including an "envelope of major earthquakes" that extends from the south only as far as 30 km north of Milford Sound. His envelope is stated to be based on *New Zealand Seismological Reports* 1955–60. The "envelope" is certainly misleading even with respect to earthquakes of this period. Although Hatherton does not define "major earthquake", it is reasonable to include in this term at least those of M5 or greater. One such shock took place 20 km to the west of the envelope in 1959, and the limit of the envelope is drawn through the epicentre of the main 1960 shock 30 km west of Big Bay, leaving several big aftershocks outside it.

In a paper mainly concerned with intermediate-depth earthquakes in south-west New Zealand, Hamilton and Evison (1967, fig. 1) gave a map of New Zealand earthquakes of $M \geqslant 4{\cdot}5$ for January to November 1964. In their fig. 4 they showed shallow-focus earthquakes of $M \geqslant 4{\cdot}0$ for June 1963 to December 1964, for south-west New Zealand.

It is surprising that neither Hatherton nor Hamilton and Evison cited earthquakes for 1961–63, published in *New Zealand Seismological Reports*. On Fig. 1 are shown all epicentres of M4 and greater in south-west New Zealand for 1955–63, covered by these published *Records*. These include two from the 1961–63 period greater than M5* and one greater than M6, all outside Hatherton's envelope.

Hatherton and, separately, Hamilton and Evison drew attention to the large (>150 milligal) positive gravity anomaly of west-central and south-west Fiordland, centred at about 45·5° S, 167·0° E. There is, however, no clear association of this with seismicity, the densest activity shown on Fig. 1 lying in an area of no significant gravity anomaly. The gravity anomaly, seismicity, and the magnetic anomaly of the east side of the Macquarie Ridge (Hatherton, 1967, fig. 4) all lie in a linear belt, and some connection between them may well exist. This may be the "active margin between the New Zealand continental mass and the Tasman Sea" (Hamilton and Evison, 1967, p. 1319), but another pertinent feature, extending well into this belt from the north-east, is the Alpine Fault. The geophysicists' discussion of the Alpine Fault seems designed to imply, rather than state, that they do not think the Alpine Fault extends south-west off shore beyond Milford Sound, as far as which it is indubitably an active fault and beyond which its trend would take it out to sea. Hatherton noted (p. 1210) "there is no evidence of its extension" beyond Milford Sound. Hamilton and Evison stated (p. 1328) "The [seismically] active region of south-west New Zealand occupies a position . . . between . . . the Macquarie Ridge and the

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*Of these two, one (44·1° S, 168·6° E) is listed in the 1962 *Report* as being M5·4, whereas it is shown as over M6 on the accompanying map.

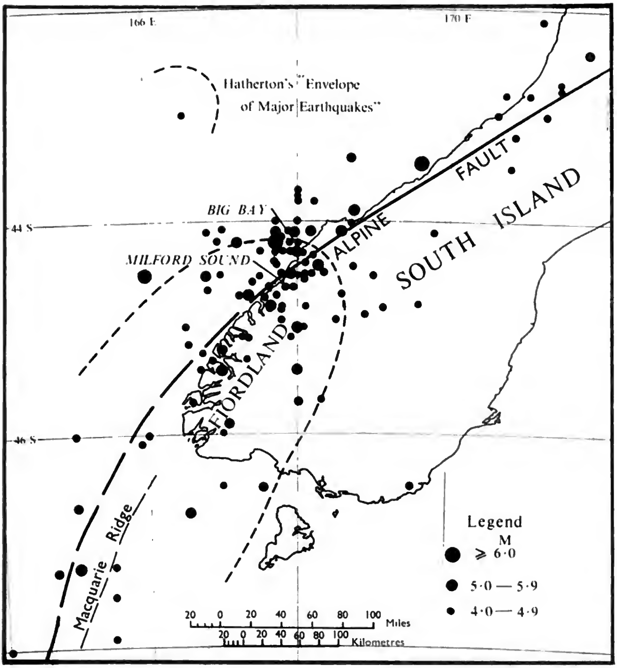

FIG. 1—1955–63 shallow and normal earthquakes in south-west New Zealand, and the probable position of the Alpine Fault.

southern extremities of the Alpine Fault and the main mountain axis". Neither of the geophysicists' papers took into account the mapping of a linear belt of coastal cataclastic rocks for 35 km south-west of Milford Sound (Wood, 1962). Beyond the known cataclastic belt, where the Alpine Fault presumably lies further off shore, its reasonable extension is south-south-west off the western side of the Macquarie Ridge; from bathymetry, such a direction seems at least as likely as the straight line at 215° from Milford Sound suggested by Barker (1967). Thus the Alpine Fault provides a structural link between the regions of geophysical and geological contrasts.

Hatherton stated (1967, p. 1210) that "over much of its recognisable length, between Milford Sound and Lake Rotoroa, the Alpine Fault has no association with known seismicity". A comparable generalisation was made by Hamilton and Evison (p. 1319), who remark on a "zone of comparatively slight activity" between a northern and a southern (Fiordland) seismic region. All the seismicity of the region will not be directly associated with the Alpine Fault, but Fig. 1 could well be interpreted as indicating some connection for much of it. The most north-easterly epicentre on Fig. 1 is more than half way from Milford Sound to Lake Rotoroa.

The accumulating geophysical data will undoubtedly lead to a better understanding of the major structures of south-west New Zealand. This understanding, however, is too far off to allow the importance of the main structural feature of the South Island, the Alpine Fault, to be discounted.

7 May 1968.

R. P. SUGGATE,
New Zealand Geological Survey,
P.O. Box 30368, Lower Hutt.

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Letter to the Editor

REPLY TO R. P. SUGGATE'S LETTER

(1)

Sir,

The purpose of our paper was to present definite evidence that earthquakes at intermediate depths occur in south-west New Zealand, and to point out that this further strengthens the interpretation of the region as a typical active margin. The Alpine Fault, where it is definitely known, is of course mainly outside the region. If the Fault can be shown to extend through it, as Dr Suggate considers reasonable, this would be of very great interest, but would not affect our results. In the meantime it should be noted that his extension of the Fault south-south-west off the western side of the Macquarie Ridge is not supported by any compelling evidence.

Our brief references to the Alpine Fault were not intended to discount its importance. The fact that the Fault connects New Zealand's two active margins may well be one of the most important features of it from the viewpoint of New Zealand geodynamics as a whole.

Dr Suggate is puzzled by our having concentrated on earthquakes that occurred after June 1963. Our reason for doing so was that the accuracy of determining earthquake foci in south-west New Zealand improved greatly in that month with the installation, mentioned in our second paragraph, of a Willmore seismograph at Monowai.

Regarding Dr Suggate's discussion of the seismicity of south-west New Zealand, it should be pointed out that the earthquake data in his Fig. 1 are not a good statistical sample for the region because they include the magnitude 7 shock of May 1960 and some of its very numerous aftershocks. This exaggerates the density of activity in the neighbourhood of Milford Sound, since magnitude 7 events occur only about once per decade, on the average, in the whole of New Zealand, and of course at a fraction of this frequency in the south-west region alone.

14 August 1968.

R. M. Hamilton,
U.S. Geological Survey,
Menlo Park, California.

F. F. Evison,
Victoria University of Wellington.

LETTER TO THE EDITOR

REPLY TO R. P. SUGGATE'S LETTER

(2)

Sir,

I did not use the earthquakes for 1961–63 for the simple reason that the New Zealand Seismological Reports for those years were not published when my paper was written (in 1965). With regard to his criticism of my "misleading" envelope Suggate should take note of the accuracy of earthquake epicentres given in the New Zealand Seismological Reports. He will

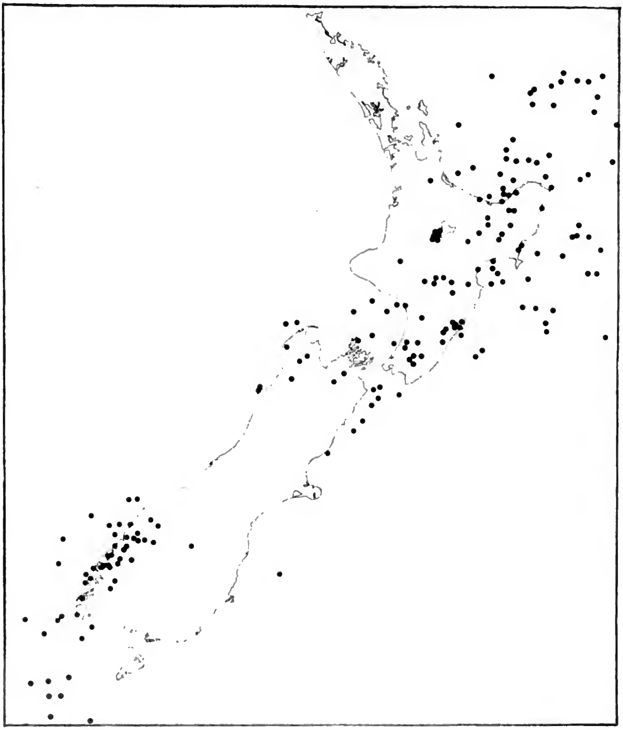

FIG. 1—Epicentres of earthquakes ⩾ M4 in the New Zealand Region for 1963 and 1964. Data from N.Z. Seismological Reports 1963, 1964.

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find that no epicentre that I have used is farther from the envelope than its estimated maximum error. The envelope of seismicity that I have drawn is certainly less misleading than one encircling all the errors in the epicentre determinations.

The upgrading of Monowai (1963) greatly improved the detection and location of earthquakes in south-west New Zealand. The normal earthquake epicentres for New Zealand for 1963 and 1964, the latest two years available, are shown in Fig. 1 and demonstrate quite clearly why New Zealand geophysicists consider that there are two seismic regions in New Zealand.

That the Alpine Fault connects these two areas is not disputed, though Suggate's extrapolation of it southwards, for a distance longer than its actual observed length, will certainly be disregarded by geophysicists. That earthquakes have occurred between the two areas is not in doubt, but they are much less frequent than in the two active regions, and may well follow a different frequency-magnitude law. That the Alpine Fault is important is also not in question. But, whereas the fault is of *paramount* importance to the geologist because of the limitations imposed on his observations, to the geophysicist it is merely *one* of the *many* manifestations of geodynamic events in the New Zealand region.

4 September 1968.

TREVOR HATHERTON,
Geophysics Division,
Department of Scientific and Industrial Research,
Wellington.

LETTER TO THE EDITOR

W.1/

A REINTERPRETATION OF THE WELLINGTON CRUSTAL REFRACTION PROFILE

Sir,

The Department of Scientific and Industrial Research with the co-operation of the Royal New Zealand Navy carried out a 177 km long, unreversed refraction profile in March 1952. This Geophysics Division project involved the recording of 11 explosions at 34 sites in the greywacke mountain ranges to the north of the city of Wellington.

Two interpretations have been published of these seismic recordings (Officer, 1955; Eiby, 1955, 1957) the conclusions being substantially in agreement—suggesting a crustal thickness of 18–19 km for this part of New Zealand.

This result placed the New Zealand crust and region in an anomalous position with respect to the rest of the world. Eiby's tables 10 and 11 show crustal thickness results for continental and oceanic regions, and New Zealand's crust, indeed, seemed to be intermediate between continental and oceanic areas prompting Eiby to propose the term "insular" to describe it.

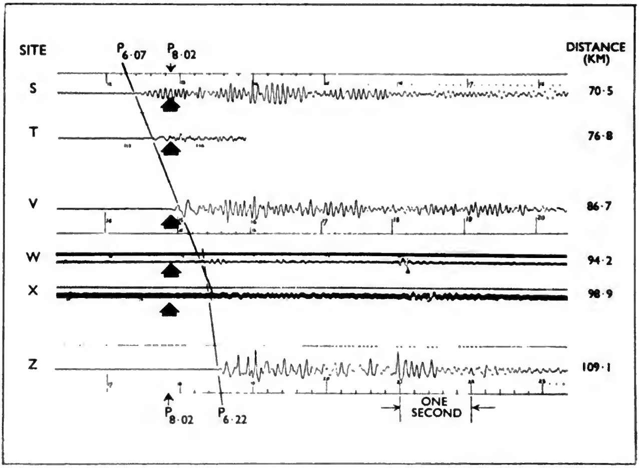

FIG. 1—The "Officer–Eiby" selection of Mohorovicic Refractions, marked by broad arrows and giving a velocity of 8·02 km/sec.

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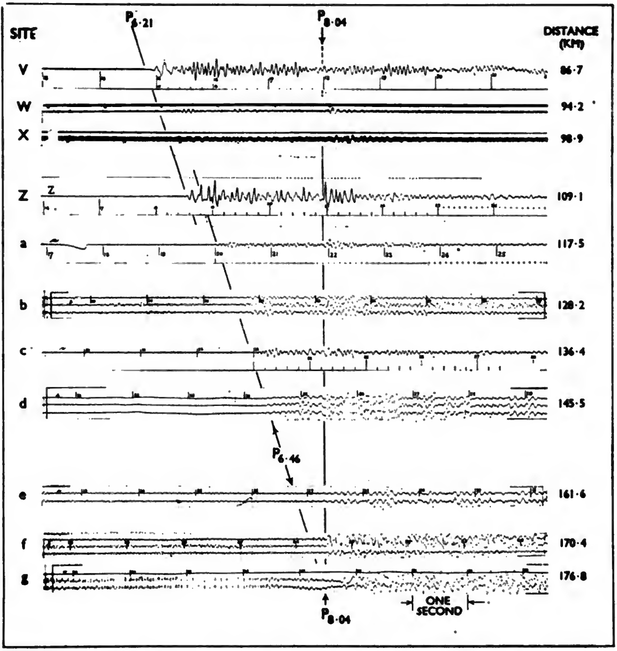

FIG. 2—The "new" set of arrivals selected as Mohorovicic Refractions, which give a velocity of 8·04 km/sec.

These considerations led me to re-examine the records of the Wellington crustal refraction profile. A new set of energetic, second arrival refraction events have been found on the recordings from 94–177 km which yield a velocity of 8·04 km/sec and, if assumed to be Mohorovicic refractions in place of those previously chosen by Officer (1955) and Eiby (1955, 1957), yield a crustal thickness for Wellington Province of 36 km.

In what follows I shall briefly describe my interpretation which is substantially similar to that of Eiby except, as stated above, with respect to the Mohorovicic refractions. These are shown in Figs. 1 and 2, the Officer–Eiby selection in Fig. 1 indicated by broad arrows. The time–distance axes have been skewed so that a velocity of 8 km/sec would be a vertical line-up. The lack of an appropriate event on the clear recording from Site Z in Fig. 1—a recording with better signal to noise ratio than its neighbouring sites—seems rather strong evidence against the validity of such a selection.

THE PENCARROW–EASTBOURNE PROFILE

The first arrival times from the uppermost layer in the Wellington profile (Table 3, 5–27 km shotpoint range) did not pass through the origin of the time–distance graph. The Pencarrow–Eastbourne profile (0·3–6·7 km shotpoint range) was produced in August 1955 to remedy this situation, with shotpoint and geophone positions being sited entirely on "undifferentiated greywackes and argillites of Permian to Jurassic age".

Fig. 3 shows the time–distance plot so obtained to which corrections for the step-back process, attributed to frequency dependent absorption with distance, must be applied. Fig. 4 shows how the periods of the first arrival waves increase with distance in both the Pencarrow and Wellington profiles out to 20 km, but the factors influencing the step-back process and the distances out to which due allowance must be made for it are rather obscure.

The writer has smoothed the Pencarrow–Eastbourne observations and Table 1 lists these values after correcting for the "step-back process".

Second order groupings are now evident by close inspection of Fig. 3 and perusal of Table 1. A velocity close to 11,500 ft/sec (3·5 km/sec) goes through the origin whilst a second of approximately 13,500 ft/sec (4·1 km/sec) is recorded from 1·2–3·0 km. This gives way to a third of 17,000 ft/sec (5·2 km/sec) at distances exceeding 3 km.

Three solutions of increasing complexity have been computed—see Table 2—assuming horizontal layering in the "greywackes". These indicate that a velocity near to 5·4 km/sec is attained at a depth of approximately 1 km from the surface which persists as a first arrival from 4–30 km. The 3·5 km/sec velocity through the origin gives way to the 4·0–4·3 km/sec material at a depth of the order of 0·1 km. In quarries in the Wellington region this is about the penetration required to note visually a change-over from brown to blue-grey "metal"—that is from weathered to unweathered rock. Velocities of the order 4·3 km/sec give way to others in excess of 5·0 km/sec at a depth of about 0·7 km.

The final by-product of the Pencarrow–Eastbourne profile allows one to calculate an average velocity for the "greywackes" using the eight layer interpretation in Table 2. Taking the time of transit for a vertically travelling wave will give a minimum velocity estimate which turns out to be 14,500 ft/sec ($4{\cdot}4_2$ km/sec) for the 2,654 ft of the seven layers involved. This average velocity will be used in the calculations for the Wellington crustal profile.

THE SEISMIC PULSES READ FROM THE MAIN CRUSTAL PROFILE

The time–distance graph of initial energies recorded on the Wellington profile splits naturally into three linear segments. The observations comprising each segment are tabulated in Tables 3, 4, and 5.

Onset quality of the seismic pulses has been tabulated also in the following tables. Three symbols have been used to characterise the arrivals depending upon the time uncertainties with which they can be read. !, i, and e are defined by uncertainties of <25, 25–100, and >100 millisecs respectively.

Text continued on page 1290

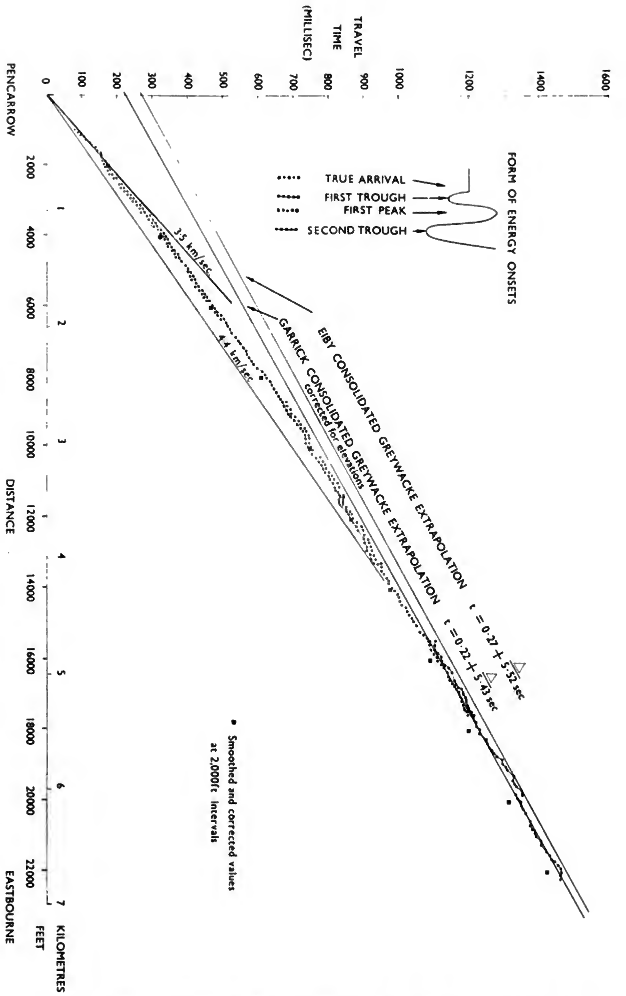

FIG. 3—The time–distance graph of the Pencarrow–Eastbourne refractions.

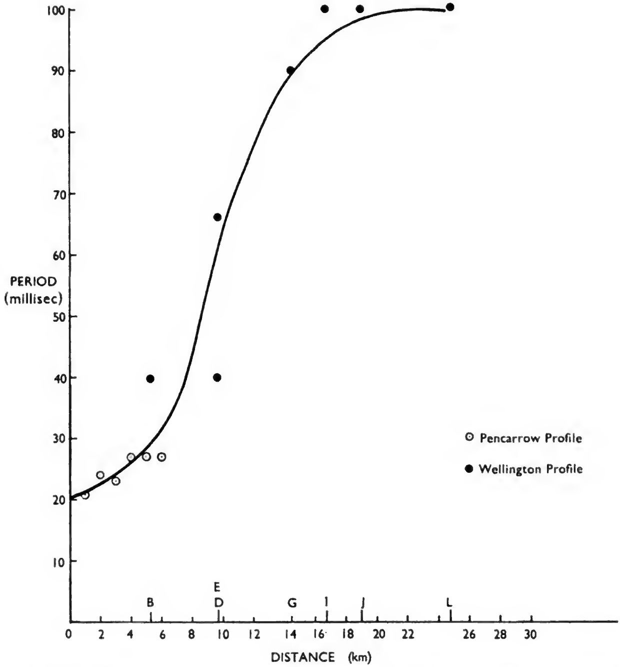

FIG. 4—The variation of period of the first arrival refractions with distance as observed on the Pencarrow–Eastbourne and Wellington crustal structure profiles.
The numeral "24" has accidentally been omitted from the distance scale

TABLE 1—The Pencarrow–Eastbourne Observations

Distance (ft)	0	2,000	4,000	6,000	8,000	9,500	
Time (msec)	0	174	324	470	614	721	
Velocities (ft/sec)	11,494	13,333	13,699	13,889	14,019	16,667	
Velocities (km/sec)	3·50	4·06	4·18	4·23	4·27	5·08	
Distance (ft)	10,000	12,000	14,000	16,000	18,000	20,000	22,000
Time (msec)	751	869	983	1,096	1,208	1,319	1,429
Velocities (ft/sec)	16,949	17,544	17,699	17,857	18,018	18,182	
Velocities (km/sec)	5·17	5·35	5·39	5·44	5·49	5·54	

TABLE 2—Three Models of Increasing Complexity and their Solutions that Approximate the Pencarrow–Eastbourne Observations

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3-Layer Approximation

V_0 constant from 0–2,000 ft = 11,500 ft/sec $t_0 = 0{\cdot}000$ sec
V_1 constant from 4,000–9,500 ft = 13,850 ft/sec $t_1 = 0{\cdot}038$ sec
V_2 constant from 11,600–22,000 ft = 17,900 ft/sec $t_2 = 0{\cdot}195$ sec

Hence $d_0 =$ 392 ft
$d_1 =$ 1,560 ft
and $d_0 + d_1 =$ 1,952 ft (0·6 km)

5-Layer Approximation

V_0 constant from 0–2,000 ft = 11,500 ft/sec $t_0 = 0{\cdot}000$ sec
V_1 constant from 2,000–6,000 ft = 13,510 ft/sec $t_1 = 0{\cdot}026$ sec
V_2 constant from 6,000–10,000 ft = 14,230 ft/sec $t_2 = 0{\cdot}048$ sec
V_3 constant from 10,000–14,000 ft = 17,240 ft/sec $t_3 = 0{\cdot}171$ sec
V_4 constant from 14,000–22,000 ft = 17,940 ft/sec $t_4 = 0{\cdot}202$ sec

Hence $d_0 =$ 285 ft
$d_1 =$ 404 ft
$d_2 =$ 1,221 ft
$d_3 =$ 627 ft
and $d_0 + d_1 + d_2 + d_3 =$ 2,537 ft (0·77 km)

8-Layer Approximation

V_0 constant from 0–2,000 ft = 11,500 ft/sec $t_0 = 0{\cdot}000$ sec
V_1 constant from 2,000–4,000 ft = 13,330 ft/sec $t_1 = 0{\cdot}024$ sec
V_2 constant from 4,000–6,000 ft = 13,700 ft/sec $t_2 = 0{\cdot}032$ sec
V_3 constant from 6,000–8,000 ft = 13,890 ft/sec $t_3 = 0{\cdot}038$ sec
V_4 constant from 8,000–10,000 ft = 14,600 ft/sec $t_4 = 0{\cdot}066$ sec
V_5 constant from 10,000–12,000 ft = 16,950 ft/sec $t_5 = 0{\cdot}161$ sec
V_6 constant from 12,000–14,000 ft = 17,540 ft/sec $t_6 = 0{\cdot}185$ sec
V_7 constant from 14,000–22,000 ft = 17,940 ft/sec $t_7 = 0{\cdot}202$ sec

Hence $d_0 =$ 273 ft
$d_1 =$ 179 ft
$d_2 =$ 159 ft
$d_3 =$ 400 ft
$d_4 =$ 904 ft
$d_5 =$ 441 ft
$d_6 =$ 298 ft
and $d_0 + d_1 + d_2 + d_3 + d_4 + d_5 + d_6 =$ 2,654 ft (0·81 km)

TABLE 3—First Arrival Refractions Through Consolidated Greywacke

Site	Shot	Charge (lb)	Distance (km)	Onset Quality	Record Quality	Elev. Corr. (msecs)	T_0 = Corrected Time (secs)	Residual $T_0 - T$ (msecs)	Remarks
*A	2	400	3·41	!	Very poor	13	0·967		
B	14	3,200	5·30	i	Poor	45	1·195	− 4	
*C	1	400	8·5	e	Terrible	......	......		
D	13	1,600	9·60	i	Fair	37	1·948	−43	
E	4	1,600	9·75	e	Poor	67	2·053	+34	
F	4	1,600	11·12	e	Terrible	63	2·207	−64	
G	4	1,600	14·50	i	Good	10	2·910	+17	
I	2	400	16·61	i	Good	5	3·320	+38	
J	2	400	18·98	i	Good	12	3·778	+60	
*K	1	400	21·9	e	Poor	13	4·367		
L	1	400	24·6	e	Poor	33	4·817	+64	
M	13	1,600	27·61	e	Fair	59	5·211	−97	
*N	2	400	28·49	e	Very poor	13	5·557		

*Omitted after simple graphing; rather a late event; not used in least squares solution.

TABLE 4—First Arrival Refractions Through the "Metamorphic" Layer

Site	Shot	Charge (lb)	Distance (km)	Onset Quality	Record Quality	Elev. Corr. (msecs)	T_0 = Corrected Time (secs)	Residual $T_0 - T$ (msecs)	Remarks
O	14	3,200	41·15	i	Good	27	7·50	− 50	
P	7	3,200	41·52	e	Very poor	27	......	......	Very noisy trace
Q	6	1,600	48·74	e	Terrible	13	......	......	Vague energy
R	7	3,200	54·59	e	Poor	19	......	......	Very noisy trace
S	6	1,600	70·50	e	Fair	10	12·39	+110	
T	13	1,600	76·81	e	Poor	27	13·32	+ 30	
U	6	1,600	80·11	e	Useless	40	......	......	
V	7	3,200	86·69	i	Good	47	14·85	− 30	
W	6	1,600	94·19	e	Fair	27	16·06	− 30	
X	7	3,200	98·85	e	Poor	12	......	......	Very noisy trace
Y	7	3,200			Useless	......	......	......	
Z	11	1,600	109·09	i	Good	33	18·48	− 10	

TABLE 5—Second and First Arrrival Refractions Through the "Intermediate" or "Basaltic" Layer; i.e., Along the Conrad Discontinuity

Site	Shot	Charge (lb)	Distance (km)	Onset Quality	Record Quality	Elev. Corr. (msecs)	T_0 = Corrected Time (secs)	Residual $T_0 - T$ (msecs)	Remarks
W	6	1,600	94·19	e	Fair	27	16·34	+ 10	
X	7	3,200	98·85	e	Poor	12	16·97	− 80	
Z	11	1,600	109·09	e	Good	33	18·74	+100	
a	10	3,200	117·50	e	Fair	87	19·87	− 70	
b	9	1,600	128·16	e	Very poor	90	21·60	+ 10	
c	9	1,600	136·39	e	Fair	113	22·95	+ 90	
d	10	3,200	145·48	e	Good	94	24·24	− 30	
e	11	1,600	161·57	e	Poor	93	......	......	Very noisy trace
f	13	1,600	170·44	e	Poor	135	28·10	− 30	
		3,200	176·75	...	Poor	133	......	......	
g	14	Approximate crossover with P_n—Not used in computations.							

TABLE 6—Second Arrival Refractions Through the Mantle; i.e., Along the Mohorovicic Discontinuity

Site	Shot	Charge (lb)	Distance (km)	Onset Quality	Record Quality	Elev. Corr. (msecs)	T_0 = Corrected Time (secs)	Residual $T_0 - T$ (msecs)	Remarks
W	6	1,600	94·19	e	Fair	27	18·88	− 50	
X	7	3,200	98·85	e	Poor	12	19·55	+ 40	
Z	11	1,600	109·09	!	Good	33	20·91	+120	
a	10	3,200	117·50	i	Fair	87	21·82	− 10	
b	9	1,600	128·16	e	Very poor	90	23·08	− 80	
c	9	1,600	136·39	e	Fair	113	24·14	− 40	
d	10	3,200	145·48	e	Good	94	25·32	+ 10	
e	11	1,600	161·57	e	Poor	93	27·22	− 90	
f	13	1,600	170·44	e	Poor	135	28·38	− 40	
g	14	3,200	176·75	e	Poor	133	29·33	+130	

A glance through Tables 3–6 is sufficient to note the emergent nature of the majority of the pulses.

The reader's attention is also drawn to the seventh column in Tables 3–6 in which elevation corrections appear. These have been computed simply as vertical travel times using a velocity of 15,000 ft/sec and are believed to be a necessary, if small, refinement to crustal velocities.

Consolidated Greywacke Refractions (Table 3)

The first linear segment extends from 3·4 to 28·5 km. Its possible extension to greater distances as second arrival energy has been sought after without success. The link-up of these observations with the Eastbourne–Pencarrow profile is almost exact (Fig. 3), this circumstance being responsible for ascribing these refractions "to a consolidated greywacke layer".

"Metamorphic" Layer Refractions (Table 4)

Although 12 recording sites were occupied in the sector 40–110 km, it is unfortunate that for various reasons only half of these times were usable in defining this segment of the travel time curve. The velocity obtained from six observations only cannot be said to be "well determined" but it is of the order to be expected for "metamorphic" rocks.

Conrad Refractions (Table 5)

These emergent arrivals yield a third linear segment of the time–distance curve. Up to 140 km their first arrival nature is due to the negligible energy carried in the true first arrival, the "metamorphic" pulse. The strong recording from Site Z exemplifies this by displaying both events.

It seems probable that these arrivals correspond to the P* of natural earthquake seismology and travel in the "intermediate" or "basaltic" sima of the crust.

Mohorovicic Refractions (Table 6)

It is now asserted that the alternative "energy line-up" to be found on the crustal profile readings (Fig. 2), is in fact the refracted energy from the Mohorovicic discontinuity. This energy line-up consists solely of second arrival pulses. The four recordings from sites W, X, Z, and a (94–118 km range) all show very prominent pulses of energy 2½–3 sec after the first arrival onsets, which continue to be observed on all recordings out to the limit of the crustal profile at site g (177 km). At this latter distance the Mohorovicic refraction merges with the true first arrival, the refraction along the Conrad discontinuity. Table 6 lists these second arrival refractions through the mantle. The spike onset to the recording from the site Z is probably fortuitous but the energy in the 5–6 cycle event is unmistakable.

LEAST SQUARES SOLUTION

The seismic observations on the time–distance graph all appear to lie along four linear segments. The four straight lines that have been fitted to these observations in Tables 3, 4, 5, and 6 have been found by the method of least squares. All observations have been treated as of equal weight in the least squares fit. Four observations in Table 3, however, have been omitted from the least squares solution after graphical inspection showed them to be rather late. Also tabulated in Tables 3, 4, 5, and 6 are the residuals in milliseconds from the least squares solution, computed in the conventional sense of "observed minus calculated" times. Adding the equation for the average velocity of the unconsolidated "greywackes" we may write the results as follows:

$$t = 0{\cdot}00 + \frac{\triangle}{4{\cdot}4_2} \qquad \text{assumed}$$

$$t = 0{\cdot}22 + \frac{\triangle}{5{\cdot}4_3} \qquad \pm\, 0{\cdot}057$$

$$t = 0{\cdot}93 + \frac{\triangle}{6{\cdot}2_1} \qquad \pm\, 0{\cdot}059$$

$$t = 1{\cdot}76 + \frac{\triangle}{6{\cdot}4_6} \qquad \pm\, 0{\cdot}067$$

$$t = 7{\cdot}22 + \frac{\triangle}{8{\cdot}0_4} \qquad \pm\, 0{\cdot}077$$

where t is in seconds and $\triangle$ in kilometres.

In the right-hand column are tabulated the standard errors, which are computed from n residuals $r_1, r_2 \ldots r_n$, in the usual manner.

$$\text{i.e., Standard Error} = \left\{\frac{\overset{2}{r_1} + \overset{2}{r_2} + \ldots \overset{2}{r_n}}{n-1}\right\}^{\frac{1}{2}}$$

They show that all four refractors are similarly well defined.

THE CRUSTAL SECTION

A crustal model may now be described consisting of four horizontal interfaces below the Earth's surface, the deepest interface being coincident with the Mohorovicic discontinuity. Four interfaces imply four layers in the crust in each of which the velocity of seismic waves is assumed to be constant.

The uppermost layer in this model is to be identified with the 1 km deep region of unconsolidated "greywackes" of average velocity $4{\cdot}4_2$ km/sec. This approximation will have no great effect on the total crustal section. With this reservation in mind, it is now possible to compute the crustal section from this model (*see* Table 7).

Average Velocities, Critical Distances, and Minimum Times in the Crust

It is possible now to calculate the average velocities of the crustal material between the various discontinuities in the crust and the surface of the Earth. Vertically travelling waves yield minimum values of average crustal velocity.

TABLE 7—The Solution of the Crustal Model

Layer 1	Unconsolidated "greywackes"	$V_1 = 4{\cdot}42$ km/sec	$T_1 = 0{\cdot}00$ sec	
2	Consolidated "greywackes"	$V_2 = 5{\cdot}43$ km/sec	$T_2 = 0{\cdot}22$ sec $\therefore$	$d_1 = 0{\cdot}42$ km
3	Metamorphic layer	$V_3 = 6{\cdot}21$ km/sec	$T_3 = 0{\cdot}93$ sec $\therefore$	$d_2 = 4{\cdot}46$ km
4	Intermediate or Basaltic layer	$V_4 = 6{\cdot}46$ km/sec	$T_4 = 1{\cdot}76$ sec $\therefore$	$d_3 = 8{\cdot}24$ km
5	Mantle	$V_5 = 8{\cdot}04$ km/sec	$T_5 = 7{\cdot}22$ sec $\therefore$	$d_4 = 22{\cdot}59$ km

Consequently, Depth to Conrad Discontinuity $= d_1 + d_2 + d_3 = 13{\cdot}12$ km
and Depth to Mohorovicic Discontinuity $= d_1 + d_2 + d_3 + d_4 = 35{\cdot}71$ km

Average Velocities—Surface to Conrad Discontinuity

Average velocity for vertically travelling wave = 5·6 km/sec
Average velocity for wave critically refracted at Conrad discontinuity = 6·0 km/sec

Average Velocities—Surface to Mohorovicic Discontinuity

Average velocity for vertically travelling wave = 6·15 km/sec
Average velocity for wave critically refracted at Mohorovicic discontinuity = 6·25 km/sec
Critical distance for Conrad refraction = 72 km
Critical distance for Mohorovicic refraction = 90 km
Time for Vertical Reflection from the Conrad discontinuity = 4·70 sec
Time for Vertical Reflection from the Mohorovicic discontinuity = 11·70 sec
Minimum Time for Conrad refraction = 12·94 sec
Minimum Time for Mohorovicic refraction = 18·36 sec

These results have been computed from the crustal model and its solution described in the previous section.

REFLECTION DATA

The appearance of certain events on the seismic recordings from the Wellington profile leads one to suppose that they are reflections from some discontinuity deep in the crust. It is felt, however, that the reflection data from the Wellington profile lack the detail and coherence necessary for their adequate interpretation.

DISCUSSION AND CONCLUSIONS

In the Wellington Province of New Zealand the Earth's crust is continental in thickness. This conclusion is based anew on the records of the Wellington profile shot in March 1952, which portray a crust composed of four layers underlain by a mantle velocity of $8{\cdot}0_4$ km/sec. These layers have thicknesses of 1, 4, 8, and 23 km and corresponding velocities of 4·4, 5·4, 6·2, and 6·5 km/sec respectively. The new set of second arrival Mohorovicic events casts doubt on the validity of the "Officer–Eiby" arrivals purporting to come from the Mohorovicic discontinuity; the events have considerable energy associated with them particularly in the 90–120 km range of distances. The lack of an equivalent event on the 87 km recording may be significant in terms of critical distances for the Mohorovicic refraction.

Two other papers already published support a continental crustal thickness for New Zealand; one dealing with the thickness of the New Zealand crust using surface wave dispersion data (Thomson and Evison, 1962) and the other discussing the implications of New Zealand gravity data (Reilly, 1962). In addition, it would be inappropriate not to recall the work of

K. E. Bullen (1940) in a paper entitled "The Crustal Structure of the New Zealand Region as Inferred from Studies of Earthquake Waves". On p. 108, Bullen indicates "the most probable form of the general structure" of his 30 km crust whose correspondence with the present results is indeed noteworthy.

There is some doubt as to whether the terms "unconsolidated" and "consolidated" when applied to greywacke formations as in this paper are the most appropriate in the circumstances. Other suggested adjectives that might be used in place of "consolidated" are "unshattered" or "compressed". However, the work of Birch (1960, table 5) on New Zealand greywacke shows that the measured increases of longitudinal velocity from the Pencarrow Profile is complicated by factors other than pressure increase alone.

It is of interest, structurally, to note that the intermediate layer, 23 km in thickness, makes up two-thirds of the New Zealand crust.

May 1968.

R. A. GARRICK,
Geophysics Division, D.S.I.R.,
Wellington.

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LETTER TO THE EDITOR

REPLY TO R. A. GARRICK'S LETTER

Sir,

I am grateful for the opportunity to comment upon an advance proof of Mr Garrick's reinterpretation of the Wellington and Pencarrow crustal structure profiles. I have known of this work for several years and I am glad that it is at last to be published. The most significant difference from my earlier result is the identification of refraction arrivals believed to originate at a Mohorovičić discontinuity at normal continental depth. This interpretation would agree with values obtained from gravity and surface-wave studies that were not available to Officer or to me. Consequently I believe that Garrick's interpretation must now be considered definitive. It must, however, be remembered that there has been no convincing demonstration that the "crust" measured by the different techniques is in all cases identical.

The quality of the refraction arrivals that I assigned to the Mohorovičić discontinuity was not good, as the original report emphasises. Only the existence of an apparently convincing set of reflections and the fact that the velocity obtained was of the correct order justified the claim that they came from the base of the crust. Mr Garrick has had the rather heterogeneous set of original records photographically copied on a uniform time-scale. These copies clearly show the arrivals he prefers, and I agree that he should prefer them.

It remains only to regret that no comparable refraction studies have been made since 1952, and that even the original profile remains unreversed. Now that gravity and surface-wave measurements of good quality are available, the lack of good reversed crustal structure refraction profiles is a serious omission from New Zealand geophysical data.

9 September 1968.

G. A. EIBY,
Seismological Observatory,
Department of Scientific and Industrial Research,
Wellington.

LETTER TO THE EDITOR

NEW ZEALAND PERMIAN STAGES

Sir,

In a letter on Permian stages Dr Waterhouse alleges in the following sentences (1968, p. 270) that I make three errors:

"The two New Zealand stages" (Puruhauan and Waiitian) "are represented by rocks and fossils in the Takitimu column—he" (J.D.B.) "errs in stating they are absent. He also errs in stating that the Telfordian is not found elsewhere in New Zealand—rocks and fossils are known. He further errs in stating that certain lithologic correlations have not been specified. . . ."

With regard to these accusations: (*a*) I nowhere suggest that these two stages are absent from the Takitimu area. On the other hand Dr Waterhouse has stated, ". . . But the fourth" (Puruhauan) "is represented in the Takitimu area by meagre faunas, and the fifth" (Waiitian) "is so far as is known unrepresented by faunas or beds" (Waterhouse, 1967, p. 164). (*b*) The original paper (Waterhouse, 1967) cited no localities outside the Takitimu area where Telfordian faunas occurred. Reference was made to plant fossils recorded by McQueen (1954) as possibly Telfordian, although McQueen could only suggest a middle Devonian to Carboniferous age. The "Telfordian faunule" from Nelson mentioned in Dr Waterhouse's letter (p. 272) is not cited in the paper. (*c*) I wrote of unspecified stratigraphic correlation not lithologic correlation, a significant difference in the context used (cf. Waterhouse, 1967, p. 165).

Dr Waterhouse wrongly implies (1968, p. 272) that I asserted Permian paleotemperatures in Australia were constant. I suggested that cool and warm water faunas persisted in some regions, a conclusion which his letter appears to support. I did not suggest that Dr Waterhouse was attempting to establish the New Zealand Permian as a world type section (p. 272)—the term standard section was used throughout—however, I feel that there is sufficient justification (1967, pp. 162, 163, and 178) for considering the world wide implications of the proposal.

Many of Dr Waterhouse's points are arguable, but let me repeat that while I think his work on New Zealand Permian sequences (lithostratigraphy) and faunas (biostratigraphy) are of the greatest value, I regret that they have now been disguised as chronostratigraphy.

10 June 1968.

J. D. BRADSHAW,
Department of Geology,
University of Canterbury.

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